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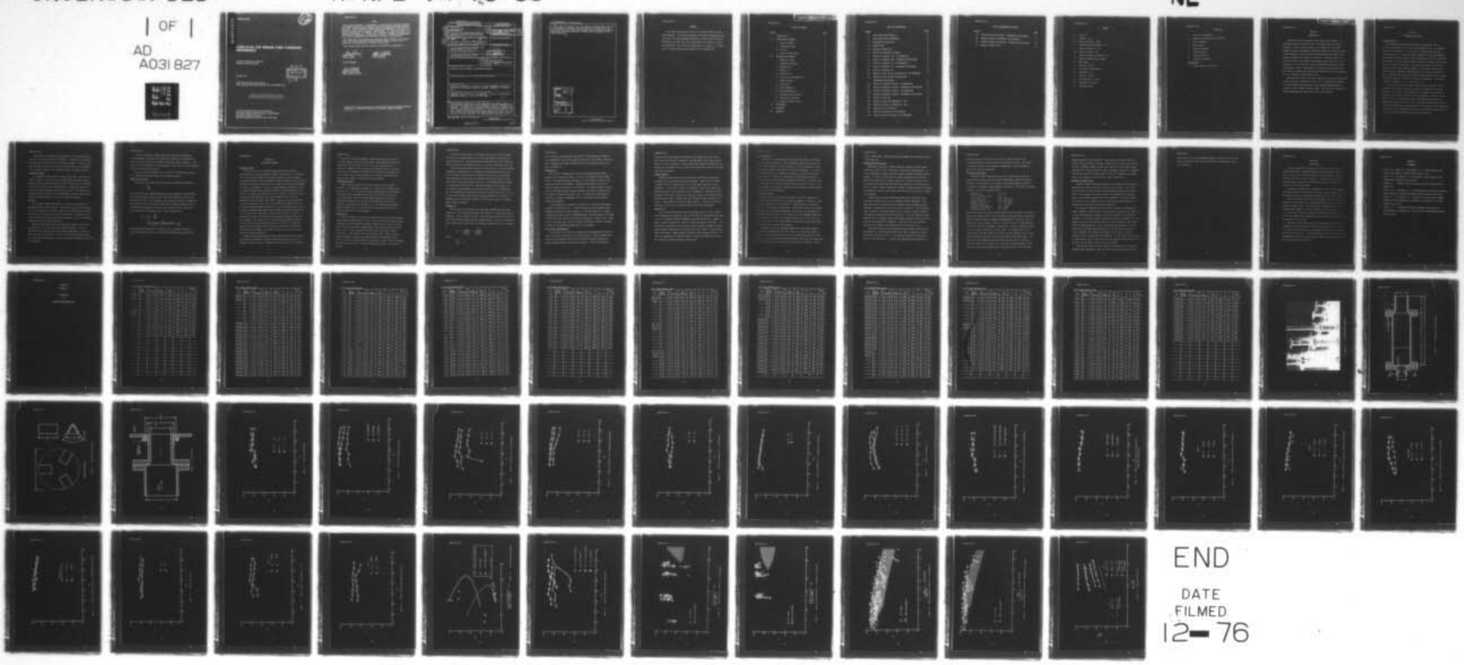

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LARGE SCALE LOW PRESSURE DUMP COMBUSTOR PERFORMANCE

RAMJET TECHNOLOGY BRANCH
RAMJET ENGINE DIVISION

AUGUST 1976

TECHNICAL REPORT AFAPL-TR-76-53
FINAL REPORT FOR PERIOD MARCH 1975 to DECEMBER 1975

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AN EXPERIMENTAL INVESTIGATION HAS BEEN CONDUCTED EXTENDING PREVIOUS RESULTS OF SMALL SCALE DUMP COMBUSTORS TO LARGER COMBUSTORS (8 TO 12" D) TESTED AT LOWER PRESSURES. A PARAMETRIC STUDY WAS THEN CONDUCTED AROUND THE 12" BASELINE CONFIGURATION, WITH AND WITHOUT FLAMEHOLDERS, IN WHICH COMBUSTOR LENGTH-TO-DIAMETER (L/D), COMBUSTOR LENGTH-TO-STEP HEIGHT (L/h), CHARACTERISTIC LENGTH (L*), FUEL INJECTOR TYPE, INLET TEMPERATURE AND CHAMBER PRESSURE WERE VARIED. LEAN BLOW-OUT LIMIT, COMBUSTION EFFICIENCY, AND COMBUSTOR PRESSURE DROP WERE OBTAINED

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20. FROM THESE RUNS USING JP-4 FUEL AND COMPARED TO PREVIOUS SMALL SCALE DATA. A LIMITED NUMBER OF ADDITIONAL TESTS WERE CONDUCTED WITH SHELLDYNE-H FUEL. RESULTS SHOW THAT GOOD COMBUSTION EFFICIENCIES CAN BE ACHIEVED WITH RELATIVELY LOW BLOCKAGE FLAMEHOLDERS RESULTING IN HIGHER OVERALL PERFORMANCE FOR THE LARGER COMBUSTORS.

FOREWORD

This report contains the results of an in-house effort on ramjet dump combustors. The work was performed in the Ramjet Technology Branch of the Air Force Aero-Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio, under Project 3012, Task 3012-12, and Work Unit 3012-12-08. The effort was conducted by R. R. Craig, P. L. Buckley, and F. D. Stull during the period March 1975 to December 1975.

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LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT'D)

SYMBOLS

A	Area-in^2
D	Diameter - in
f/a	Fuel-to-Air Ratio - lb/lb
h	Combustor Dump Step Height - in
L_c	Length of Combustor - in
L_N	Length of Nozzle - in
L	Effective Length of Combustor - in
L^*	Combustor Characteristic Length
M	Mach Number
P	Pressure - lb/in^2
S_a	Air Specific Stream Thrust
T	Temperature - ^oR
V	Velocity - ft/sec
W_A	Air Weight Flow - lb/sec
η_c	Combustion Efficiency
ϕ	Equivalence Ratio

SUBSCRIPTS

2	Inlet Duct to Combustor
3	Combustor Entrance After Dump Station
4	End of Combustor
5	Nozzle Throat
c	Combustion Chamber
i	Ideal Conditions
0	Ambient Conditions
t	Stagnation Conditions

Superscripts

*	Nozzle Throat or Sonic Point

SECTION I

INTRODUCTION

Current volume limited ramjet designs employ dump combustors. In this engine system, the booster rocket is integrated into the ramjet combustor to conserve missile volume. Such combustors do not contain combustor liners or conventional flameholders within the combustion region and must depend to a large extent upon recirculation zones formed by the sudden enlargement area between the inlet duct. Previous studies (1,2) conducted on small scale coaxial dump combustors have shown that a combustor L/D $\geq$ 4.5 is required to obtain good combustion efficiency unless a flameholder is used. Flameholders of relatively large blockage (>40%) were required to obtain good combustion efficiencies for shorter combustors, but at the expense of large pressure drops.

The objective of this effort was to extend the previous in-house studies on small scale dump combustors from 2" to 5" D to larger scale combustors, and to investigate the performance of lower blockage flameholders in an attempt to reduce combustor pressure losses. The results are applicable to coaxial dump combustors using fixed orifice, wall injectors.

SECTION II

EXPERIMENTAL PROCEDURE

Combustor Models

The combustor test hardware was similar to the hardware used in previous test programs (1,2), except it was largerin scale. The combustor sections were fabricated of 12" ID and 8" ID stainless steel pipe and flanged at both ends. Additional length combustor sections were available which allowed for three combustor length variations for the 12" D combustor. An assortment of water-cooled convergent nozzles was available which allowed combustor velocity to be varied. The nozzle lengths were such that they added approximately one combustor diameter to the overall combustor L/D, measured from the combustor sudden expansion section to the nozzle sonic plane. Combining the various nozzle sizes with the different length nozzles allowed the combustor L/D and L^* to be varied independently. The baseline combustors had values of L/D = 4 and $A^*/A_3 = 0.5$.

Fuel injection occurred through 8 injectors spaced every 45^o circumferentially in the wall of the inlet section. The injectors for the 12" combustors were located 4 1/8" upstream of the combustor entrance and 4" upstream of the combustor entrance for the 8" combustor. Fuel was injected normal to the air stream through various size simple tube injectors and variable area poppet type spray nozzles. The simple tube injectors were designed from previous fuel injection studies (3) to provide for fuel penetration of 16% of the inlet diameter by the time the fuel reached the dump plane at a fuel-to-air ratio of 0.06 and baseline pressure conditions.

One variation of increasing inlet diameter to 8" from the baseline value of 6" was made with the 12" D combustor. Hardware was not available to examine this effect with the 8" D combustor hardware. A photo of combustor hardware that has been tested is shown in Figure 1 and a schematic of the combustor hardware, with flameholder added, is shown in Figure 2.

Flameholder Design

All flameholder webs were 60°-V gutters with a base 1 1/4" wide, as shown in Figure 3. Three V-gutters were mounted from the inlet duct wall and distributed circumferentially every 120°. The base of the flameholder was in the same plane as the sudden expansion. Flameholder blockage was varied by varying the length of the V-gutter elements. The width of the flameholder web was chosen so that the flameholder would be operating well within its DeZubay stability loop for all operating conditions.

Test Rig

The combustor hardware was mounted on a thrust stand designed for measuring absolute levels of thrust. The movable deck of the thrust stand is 14 ft in length and 4 feet wide. The deck is suspended from 4 flexures 15 inches long, 4 inches wide and 0.036 inches thick. Calibration of the thrust stand load cell was accomplished by applying a force at the combustor centerline through a reference load cell.

Heated air was supplied from the laboratory's indirect fired furnace through twelve, 2" D flex hoses to the combustor hardware. Inlet air temperatures were monitored with cromel-alumel thermocouples, shielded to reduce recovery factor effects. Air flow rates were measured with flange tap square edge orifice plates, and fuel flow rates were measured with turbine type flowmeters.

In order to maintain a choked nozzle while operating the combustors at sub-atmospheric pressures, the nozzles were connected to the laboratory exhauster system by means of a flexible rolling seal, shown in Figure 4. The exhaust system was maintained at approximately 3 psia. Use of the seal required that all nozzles be water-cooled.

Data was recorded on magnetic tape at a rate of 40 channels per second via a Hewlett-Packard 2012B digital data acquisition system.

Combustion Efficiency

The definition of combustion efficiency used throughout this report is:

$$\eta_c = \frac{\Delta T_t}{\Delta T_{t_i}}$$

where ΔT_t is the total temperature rise across the combustor as computed from the thrust measurement and ΔT_{t_i} is the ideal total temperature rise for the measured fuel-to-air ratio as computed from equilibrium chemistry calculations. Since absolute thrust is measured, corrections for ambient pressure acting on the hardware and exhauster seal forces must be made in order to obtain the sonic air specific stream thrust, S_a^*. These corrections are:

$$S_a^* = \frac{F}{W_a} + \frac{P_o A^*}{W_a}$$

$$+ \frac{(P_o - P_{exhaust})}{W_a} \left[\frac{(A_{seal} + A_{ext})}{2} - A^* \right]$$

Three-dimensional tables of S_a^* versus T_{t_5} and P_{t_5}, computed by means of equilibrium chemistry routines, are then used to determine T_{t_5} from S_a^* and P_c.

SECTION III

DISCUSSIONS & RESULTS

Combustor Scaling

The 5" D, 8" D and 12" D combustor models were tested at baseline conditions which approximated "pressure scaling" criteria (4,5). To accomplish this, the air flow was adjusted for each size combustor so that the product of combustor chamber pressure and combustor diameter remained essentially constant. Exit nozzle throats were chosen so that the combustor velocity was approximately the same in all combustors. In order to maintain geometric similarity on overall combustor length (which includes the length of the nozzle upstream of the throat), a new nozzle was fabricated for the 5" D chamber. Previous 5" D tests had been conducted using only a very short convergent nozzle. Inlet air temperature was held constant around 1000^{o}R. Fuel-to-air ratios were selected to cover the range from .025 to .06. Due to difficulty in adjusting the air flow while using the exhauster system, air flow was not varied with fuel flow in an attempt to maintain essentially constant chamber pressures, as had been done in the previous small scale tests. Rather, a fuel-to-air ratio of .04 was arbitrarily selected as the condition for achieving the baseline pressure for each combustor. This resulted in the chamber pressure increasing slightly as the fuel-to-air ratio was increased during each test series. A spark plug, modified to burn hydrogen with air, was used as a pilot flame to ignite the fuel mixture in the chamber. The ignitor was used only to initiate the combustion and then was switched off.

Figure 5 gives the combustion efficiency results for the scaled combustor models without flameholders. Baseline conditions were 40 psia for the 5" D combustor, 25 psia for the 8" D combustor and 16.7 psia for the 12" D combustor.

It is noted that reasonable agreement in combustion efficiency exists over the entire range of fuel-to-air ratios tested. Dump combustors have now been scaled from 3" D at 66.7 psia to 12" D at 16.7 psia with good results. A smaller 2" D combustor tested at 90 psia gave comparable results at low fuel-to-air ratios, but combustion efficiency fell off markedly at the higher fuel-to-air ratios. This could have been due to the relatively large heat loss from the small combustor operating at such high pressures.

Flameholder Blockage

Figure 6 gives the combustion efficiency results for a 25% and 35% modified Y type flameholder and compares it to the basic 12" D combustor which has an L/D of 4. It is noted that the 25% blockage flameholder substantially increases the basic dump combustor performance over the entire fuel-to-air ratio range tested. Going to the 35% blockage flameholder increases the combustion efficiency by 6 to 8 counts at the higher fuel-to-air ratios. In comparison, it was found that the small scale 5" D combustor required flameholder blockages in excess of 35% in order to achieve performance that was much better than the basic dump combustor.

Combustor L/D

The 12" D combustor, with and without flameholders, was tested with different length chambers varying from 18" to 54" in order to determine the combustor length-to-diameter effect on combustor performance. Adding the 12.5" length of the convergent nozzle to these actual chamber lengths gives an effective range of L/D's from 2.5 to 5.5. Test conditions remained the same as during the combustor scaling tests. These results are shown in Figures 7 and 8. Figure 7 shows a strong L/D effect on the basic dump combustor without a flameholder, with an L/D of 5.5 required to achieve combustion efficiencies of 90%. This is in agreement with previous small scale 5" D results in which an L/D between 4.5 and 6.0 was required.

It should be stated that the combustion efficiencies plotted throughout this report are obtained directly from thrust measurements and are not corrected for heat loss. Previous measurements have shown that these combustion efficiencies can be increased by about 3% to account for combustor heat loss.

Figure 8 shows much improved results with the addition of the 25% blockage flameholder, although there is a tendency for combustion efficiency to fall off at the high fuel-to-air ratios, especially for the short L/D combustor. This improvement is better than was achieved with the 44% blockage Y flameholder used in the previous small scale tests. The flameholders were similar in configuration except that the three webs extended into the center of the duct and were joined together for the high blockage small scale flameholder. Thus, while comparable performance was obtained at similar L/D's for the 5" and 12" basic dump combustor under pressure scaling conditions, the addition of flameholders was not directly scalable, with the larger combustor achieving higher overall efficiency.

Combustor L^*

Previous small scale studies, with and without flameholders, had shown combustor L/D to be much more important than combustor L^*, especially for short combustors. Figure 9 shows the result of varying nozzle throat area from about 50% to 60% while maintaining combustor length constant. Due to the configuration of the nozzle used in these tests, the following equation was used in computing L^*:

$$L^* = L_c \left[\frac{A_3}{A^*}\right] + L_N \left[\frac{A_4}{A^*}\right]$$

where

$$\frac{A_4}{A^*} = 1$$

It is noted that the 50% nozzle throat area ($L^* = 85$) resulted in somewhat better performance over the mid range of fuel-to-air ratios tested. When the 25% Y flameholder was added, performance for the two nozzles was about the same, see Figure 10.

Combustor L/h

The effects of changing inlet area ratio while maintaining constant combustor L/D are shown in Figure 11 for the 12" D combustor without flameholder. Decreasing the dump step height, h, at the combustor entrance has a significant effect on performance. Decreasing step height form 3" to 2" improved combustion efficiency 5 to 10 points. Also shown in Figure 11 is the effect of reducing combustor length-to-diameter ratio while holding constant the combustor length-to-step height ratio. For this case, even though the combustor L/D change is significant, there is relatively little change in combustor performance.

It thus appears that combustor L/h is more of a controlling performance parameter than combustor L/D. It would also seem that there should be some optimum step height for a given combustor. If the step height is too small, a flameholding region cannot be established, and if the step height is too large, the flow will never come in contact with the combustor or nozzle walls. It may be that the optimum step size is the smallest one which is capable of holding a flame over the desired operating range of the combustor.

Fuel Injector Configuration

The effects of fuel injector configuration were investigated for both the fixed orifice tube injectors and the pintel injectors. Figure 12 shows these results for the baseline .059" D fixed orifice fuel injector along with a smaller diameter injector and the pintel injector. Both of the alternate

injectors give slightly higher performance at the higher fuel-to-air ratios. When tested with the 25% Y flameholder, the differences in the results became smaller, as seen in Figure 13. Previous small scale results had shown that the pintels did not atomize the fuel as well at low fuel-to-air ratios as the simple fixed orifice injectors.

Chamber Pressure

Combustor pressure was varied from baseline conditions by increasing or decreasing the air mass flow through the combustor. These results are shown in Figures 14 and 15, respectively, for the basic dump combustor and 25% Y flameholder. Little effect is noted on performance, except when tested below baseline pressure for the combustor with the flameholder. Although not shown, pressures on the order of 10 psia and lower had a similar effect when the 35% Y flameholder was tested. Similar tests were performed using the pintel fuel injectors. These results are shown in Figure 16 and 17. Very poor results were obtained at 10 psia using the pintel nozzles without the flameholder.

Type of Fuel

All of the preceding results had been obtained using JP-4 fuel. Several runs at baseline test conditions, and at lower inlet air temperatures, were made on the 12" D combustor without flameholder using Shelldyne-H fuel. Figure 18 shows a comparison between JP-4 and RJ-5 results for baseline conditions. It is noted that the combustion efficiencies are about the same, although JP-4 gives slightly higher efficiencies at the higher fuel-to-air ratios. In the previous small scale studies, slightly higher efficiencies were achieved with RJ-5. At inlet air temperatures of 1000°R and above, it may be concluded that JP-4 and RJ-5 fuels give comparable combustion performance.

Inlet Temperature

Combustor inlet air temperature was varied from 1000°R to 750°R with the 12" D baseline combustor without flameholder using both JP-4 and RJ-5 fuels. These results are shown in Figures 19 and 20, respectively. Lower combustion efficiencies are observed at the lower temperature. In case of RJ-5 a rapid decrease in combustion efficiencies is noted for fuel-to-air ratios above .05. These are in agreement with the previous small scale results, except that the drop-off in combustion efficiency at 750°R occurred at a lower fuel-to-air ratio and was more severe for the 5" D tests. This drop in combustor efficiency is attributed to an evaporation limited process under low temperature conditions.

Flame Stabilization

Blowout limits were measured for several of the 12" D combustor configurations and are plotted versus a stability parameter in Figure 21. Also shown for comparison is the correlation of premixed data for conventional disk, cone, and hemisphere flameholders. Lean blowout limits are correlated quite well with this stability parameter and are in general agreement with the previous small scale data. Rich blowout limits are somewhat higher than those obtained on the small scale hardware and may be due to the fact that the fuel injectors for the large hardware were further from the dump station than they were in the small scale hardware.

The addition of the 25% blockage flameholder to the larger hardware significantly increased the fuel-to-air ratio at lean blowout as shown in Figure 21. This effect was not present in the small scale tests with flameholders. The only apparent difference between the small scale and large scale tests is the location of the fuel injectors upstream of the dump, 2 1/2" vs

4 1/8", respectively. Both combustors were designed for the same penetration at the dump plane.

Premixed Fuel-Air Mixtures

Many times in testing of scaled combustors, geometric effects become obscured by effects of fuel penetration, atomization and vaporization. It is thus desirable to examine parametric effects employing a premixed fuel-air mixture. In order to obtain the best possible premixed fuel-air mixture, within the confines of the present thrust stand, fuel was injected into the air stream at the point where flex hoses were connected to the thrust stand. This is a highly turbulent region with a number of stagnant regions as evidenced by flashback occurring to this region with several of the combustor configurations employed.

Typical results obtained from these premixed fuel-air mixture tests are shown in Figure 22 for the 12" D combustor without flameholder. Very long combustors are required for good performance and performance tends to peak near a stoichiometric fuel-to-air ratio, as expected. For the baseline case, the effect of increased combustor L/D is almost a constant difference in combustion efficiency with fuel-to-air ratio. With the premixed fuel-air mixture there is a dramatic change in performance difference with fuel-to-air ratio for the different L/D combustors. This effect has been previously obscured by the change of fuel penetration with fuel-to-air ratio.

Lean blowout limits with the premixed mixtures tended to increase with decreasing L/D. Increasing nozzle area ratio tended to magnify the effect. With a 50% nozzle and an L/D of 4, lean blowout occurred at a fuel-to-air ratio of 0.033 under baseline pressures and temperatures and increased to a

fuel-to-air ratio of 0.035 with an L/D of 2.5. With a 70% nozzle the corresponding values of fuel-to-air ratio were 0.031 and 0.042. This effect is apparently caused by the incomplete establishment of the recirculation zone for the short L/D combustors.

Generalized Performance

Performance results obtained from the 12" D combustor tests with the baseline fuel injectors, with and without flameholders, using JP-4 fuel were analyzed on the same basis as the previous small scale combustor results in an attempt to investigate single parameter correlations. The range of variables included in this data are listed below:

Combustor L/D	2.5 → 5.5
Nozzle Area Ratio, A^*/A_3	.48 → .60
Inlet Velocity, V_2	610 → 1490 ft/sec
Combustor Velocity, V_3	155 → 340 ft/sec
Chamber Pressure, P_c	7 → 23 psia
Combustor Inlet Temp, T_{t_2}	290 → 540°F
Fuel-to-Air Ratio, f/a	.025 → .065

Results from these tests showed similar trends as those obtained in the earlier small scale combustor tests. Poor correlation was obtained when η_c was plotted against the burner severity parameter, $W_A/A^*(T_{t_2}/1000)^2$, where W_A is the air weight flow. This is shown in Figures 23 and 24 for the 12" D dump combustors without and with 25% Y flameholder, respectively. A range of test data covered by the 5" D small scale results is also given. It is noted that the 12" D tests covered much lower values of the burner severity parameter (due to lower chamber pressures) than were achieved in the earlier small scale tests. The addition of the flameholder merely increased the upper limit of combustor efficiency obtained at a given value of the burner severity parameter. Somewhat better results were obtained when a modified version to the well-known

Longwell parameter (6) was employed. These results are shown in Figures 25 and 26. Again the range of test data covered by the 5" D small scale results is given. Agreement between the small scale and 12" D tests results appears reasonable for the dump combustors without flameholder (Figure 25). Combustion efficiencies consistently appear higher for the 12" D combustors with flameholder, when compared to the small scale results (Figure 26).

Combustor Pressure Losses

Combustor pressure losses are determined from measured static pressures, mass flows and thrust rather than from total pressure rakes. This method had been found to be more reliable and consistent than using total pressure probes. The combustor inlet total pressure is computed from the measured inlet static pressure, mass flow and total temperature. The total pressure at the nozzle exit is computed from the throat area and the combustor total temperature as calculated from the measured thrust.

The combustor pressure recovery for several combustor configurations is shown in Figure 27, plotted against the heat addition parameter $S_a^* / \sqrt{T_{t_2}}$. For constant area combustion, pressure recovery will decrease as heat addition increases. For the dump combustor, pressure losses are a combination of aerodynamic losses plus heat addition losses with the aerodynamic losses usually being the dominating factor. Thus, as heat addition increases, for a given nozzle size, inlet Mach number decreases and the reduced dump aerodynamic losses overshadow the increased heat addition losses; hence, combustor pressure recovery increases with heat addition. For the largest inlet tested, the above effects tend to cancel each other and pressure recovery remains fairly constant over the range of fuel-to-air ratios tested.

The pressure recovery for the 5" and 12" D combustors are in excellent agreement when comparing the same inlet area ratios and nozzle area ratios.

Flameholders with greater blockage were used in the 5" tests so that the pressure recovery is lower than that obtained with flameholders in the 12" D combustors.

SECTION IV

CONCLUSIONS

Pressure scaling may be applied (with caution) to dump combustors without flameholders. Combustor performance with flameholders does not appear to scale, with the larger combustors achieving higher combustion efficiencies than the smaller combustors. In addition, pressure drops are much higher in small scale combustors where larger blockages are required for flame stabilization.

In general, the addition of flameholders to short L/D dump combustors increases performance substantially and tends to reduce differences caused by single variations in dump combustor geometry and operating conditions.

Combustor length-to-step height (L/h) appears to be a more important parameter in dump combustors of varying dump ratios (A_2/A_3) than combustor length-to-diameter (L/D). The length of the convergent portion of the nozzle should be added to the basic combustor length in defining L.

JP-4 and RJ-5 fuels give comparable combustion performance except at low inlet temperatures (750^{o}R) where RJ-5 performance decreases rapidly with high fuel-to-air ratios.

Combustion efficiencies measured in premixed dump combustors without flameholders show that combustor L/D has a strong influence on performance at lean fuel-to-air ratios and a much smaller influence at near stoichiometric fuel-to-air ratios. Fuel injection near the dump section can greatly overshadow this effect by maintaining the combustor recirculation zone at a near stoichiometric fuel-to-air ratio.

SECTION V

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SECTION VI

APPENDIX A

TABULATION OF COMBUSTOR PERFORMANCE DATA

Subscale Dump Combustor Data

Test	Flame Holder	D_2	L_c (inches)	D^*	$\dot{W}_a$ (#/sec)	T_{t2} (°R)	f/a	η_c	P_{t5}/P_{t2}
Scaling	0	2.5	15	3.47	3.82	1024	.0251	.753	.745
(5"D_3)	0	2.5	15	3.47	3.48	1024	.0328	.756	.770
"	0	2.5	15	3.47	3.24	1023	.0408	.848	.804
"	0	2.5	15	3.47	3.11	1021	.0465	.818	.800
"	0	2.5	15	3.47	2.98	1016	.055	.815	.811
Scaling	0	4	24	5.58	5.60	995	.0246	.756	.746
(8"D_3)	0	4	24	5.58	5.55	995	.0301	.818	.776
"	0	4	24	5.58	5.59	995	.0349	.764	.780
"	0	4	24	5.58	5.54	996	.0402	.777	.797
"	0	4	24	5.58	5.57	997	.0452	.849	.810
"	0	4	24	5.58	5.54	1001	.0506	.835	.811
"	0	4	24	5.58	5.50	1002	.0566	.843	.819
"	0	4	24	5.58	5.49	1005	.0617	.840	.826

12" D Dump Combustor Data

Test	Flame Holder	D_2	L_c (Inches)	D^* (Inches)	$\dot{W}_a$ (#/sec)	T_{t2} (°R)	f/a	η_c	P_{t5}/P_{t2}
Scaling	0	6	36	8.32	8.01	1013	.0249	.757	.739
(12"D_3)	0	6	36	8.32	8.04	1013	.0314	.793	.774
"	0	6	36	8.32	8.06	1014	.0360	.775	.782
"	0	6	36	8.32	8.10	1014	.0411	.833	.800
"	0	6	36	8.32	8.15	1013	.0458	.804	.807
"	0	6	36	8.32	8.09	1014	.0510	.807	.816
"	0	6	36	8.32	8.11	1013	.0559	.801	.825
"	0	6	36	8.32	8.06	998	.0625	.780	.827
Blockage	25%	6	36	8.32	8.04	1004	.0258	.958	.627
Blockage	25%	6	36	8.32	8.01	1005	.0308	.956	.653
Blockage	25%	6	36	8.32	8.02	1005	.0365	.947	.673
Blockage	25%	6	36	8.32	8.01	1006	.0415	.934	.692
Blockage	25%	6	36	8.32	8.04	1006	.0459	.926	.707
Blockage	25%	6	36	8.32	8.03	1008	.0522	.890	.720
Blockage	25%	6	36	8.32	8.02	1009	.0572	.878	.727
Blockage	25%	6	36	8.32	8.01	1009	.0624	.871	.735
Blockage	35%	6	36	8.32	8.13	983	.0255	.943	542
Blockage	35%	6	36	8.32	8.11	983	.0312	.957	.577
Blockage	35%	6	36	8.32	8.05	983	.0368	.977	.605
Blockage	35%	6	36	8.32	8.10	983	.0411	.963	.622
Blockage	35%	6	36	8.32	8.02	984	.0464	.983	.640
Blockage	35%	6	36	8.32	7.96	998	.0519	.967	.655
Blockage	35%	6	36	8.32	7.95	999	.0574	.956	.670
Blockage	35%	6	36	8.32	8.02	1000	.0616	.935	.678

12" D Dump Combustor Data

Test	Flame Holder	D_2	L_c (inches)	D^*	$\dot{W}_a$ (#/sec)	T_{t2} (°R)	f/a	η_c	P_{t5}/P_{t2}
L/D	0	6	54	8.32	7.94	1007	.0267	.858	.757
L/D	0	6	54	8.32	7.93	1009	.0322	.861	.784
L/D	0	6	54	8.32	7.93	1011	.0369	.915	.800
L/D	0	6	54	8.32	7.95	1011	.0416	.894	.809
L/D	0	6	54	8.32	7.95	1012	.0471	.884	.818
L/D	0	6	54	8.32	7.94	1012	.0528	.863	.823
L/D	0	6	54	8.32	7.97	1011	.0572	.851	.828
L/D	0	6	54	8.32	7.91	1007	.0631	.842	.841
L/D	0	6	18	8.32	7.79	1016	.0325	.383	.675
L/D	0	6	18	8.32	7.81	1015	.0370	.660	.762
L/D	0	6	18	8.32	7.83	1014	.0369	.664	.760
L/D	0	6	18	8.32	7.86	1015	.0425	.627	.771
L/D	0	6	18	8.32	7.89	1018	.0475	.674	.784
L/D	0	6	18	8.32	7.90	1019	.0521	.671	.791
L/D	0	6	18	8.32	7.88	1020	.0574	.653	.788
L/D	0	6	18	8.32	7.83	1021	.0632	.636	.793
L/D	25%	6	54	8.32	7.81	1045	.0264	.965	.626
L/D	25%	6	54	8.32	7.84	1045	.0325	.951	.656
L/D	25%	6	54	8.32	7.84	1044	.0377	.946	.677
L/D	25%	6	54	8.32	7.85	1043	.0425	.952	.696
L/D	25%	6	54	8.32	8.02	1012	.0465	.945	.713
L/D	25%	6	54	8.32	8.05	1012	.0514	.929	.726
L/D	25%	6	54	8.32	8.02	1011	.0573	.920	.738
L/D	25%	6	54	8.32	8.00	1011	.0625	.911	.747

12" D Dump Combustor Data

Test	Flame Holder	D_2	L_c (Inches)	D^*	$\dot{W}_a$ (#/sec)	T_{t2} (°R)	f/a	η_c	P_{t5}/P_{t2}
L/D	25%	6	18	8.32	7.89	1026	.0270	.885	.616
L/D	25%	6	18	8.32	7.92	1023	.0317	.885	.642
L/D	25%	6	18	8.32	7.86	1021	.0378	.888	.668
L/D	25%	6	18	8.32	7.85	1018	.0429	.873	.683
L/D	25%	6	18	8.32	8.05	994	.0463	.840	.689
L/D	25%	6	18	8.32	8.08	994	.0504	.822	.699
L/D	25%	6	18	8.32	8.17	995	.0555	.785	.705
L/D	25%	6	18	8.32	8.10	1002	.0622	.766	.707
L*	0	6	36	9.25	9.86	1014	.0249	.776	.604
L*	0	6	36	9.25	9.83	1014	.0295	.761	.630
L*	0	6	36	9.25	9.87	1014	.0346	.742	.654
L*	0	6	36	9.25	9.85	1015	.0391	.737	.673
L*	0	6	36	9.25	9.86	1014	.0437	.729	.689
L*	0	6	36	9.25	9.88	1014	.0489	.717	.702
L*	0	6	36	9.25	9.85	1014	.0539	.732	.718
L*	0	6	36	9.25	9.86	1013	.0589	.783	.736
L*	25%	6	36	9.25	9.93	997	.0249	.876	.494
L*	25%	6	36	9.25	9.93	996	.0295	.934	.534
L*	25%	6	36	9.25	9.92	996	.0344	.940	.561
L*	25%	6	36	9.25	9.91	996	.0389	.930	.577
L*	25%	6	36	9.25	9.85	1001	.0434	.915	.592
L*	25%	6	36	9.25	9.93	1001	.0487	.912	.609
L*	25%	6	36	9.25	9.93	1000	.0533	.905	.624
L*	25%	6	36	9.25	9.89	998	.0588	.877	.638

12" D Dump Combustor Data

Test	Flame Holder	D_2	L_c (inches)	D^*	$\dot{W}_a$ (#/sec)	T_{t2} (°R)	f/a	η_c	P_{t5}/P_{t2}
L/h	0	8	36	8.32	7.95	1023	.0261	.834	.957
L/h	0	8	36	8.32	7.94	1025	.0316	.885	.961
L/h	0	8	36	8.32	7.94	1027	.0367	.907	.962
L/h	0	8	36	8.32	7.96	1030	.0420	.905	.957
L/h	0	8	36	8.32	8.03	1032	.0464	.901	.960
L/h	0	8	36	8.32	7.98	1031	.0517	.913	.969
L/h	0	8	36	8.32	7.98	1030	.0570	.912	.967
L/h	0	8	36	8.32	8.10	1028	.0615	.886	.964
L/h	0	8	18	8.32	7.53	1065	.0275	.732	.943
L/h	0	8	18	8.32	7.49	1071	.0340	.804	.947
L/h	0	8	18	8.32	7.54	1075	.0384	.810	.947
L/h	0	8	18	8.32	7.56	1079	.0437	.816	.951
L/h	0	8	18	8.32	7.50	1084	.0496	.829	.957
L/h	0	8	18	8.32	7.52	1088	.0544	.818	.945
L/h	0	8	18	8.32	7.55	1094	.0600	.786	.946
L/h	0	8	18	8.32	7.51	1098	.0661	.776	.942

12" D Dump Combustor Data

Test	Flame Holder	D_2	L_c (inches)	D^*	$\dot{W}_a$ (#/sec)	T_{t2} (°R)	f/a	η_c	P_{t5}/P_{t2}
Fuel Inj.	0	6	36	8.32	8.01	1024	.0256	.773	.746
(.046D)	0	6	36	8.32	8.01	1024	.0318	.789	.777
"	0	6	36	8.32	7.98	1024	.0374	.771	.789
"	0	6	36	8.32	8.01	1025	.0421	.828	.807
"	0	6	36	8.32	8.04	1025	.0464	.818	.812
"	0	6	36	8.32	8.03	1025	.0520	.828	.823
"	0	6	36	8.32	8.01	1017	.0568	.837	.828
"	0	6	36	8.32	8.03	1018	.0620	.848	.835
Fuel Inj.	0	6	36	8.32	8.01	1015	.0265	.745	.727
(Pintel)	0	6	36	8.32	7.98	1016	.0315	.773	.755
"	0	6	36	8.32	8.03	1018	.0365	.791	.772
"	0	6	36	8.32	8.00	1020	.0408	.840	.789
"	0	6	36	8.32	7.96	1021	.0466	.858	.806
"	0	6	36	8.32	8.03	1021	.0508	.834	.805
"	0	6	36	8.32	7.98	1022	.0566	.844	.814
"	0	6	36	8.32	8.01	1018	.0623	.834	.826
Fuel Inj.	25%	6	36	8.32	7.88	1006	.0255	.954	.623
(.046D)	25%	6	36	8.32	7.92	1007	.0324	.938	.658
"	25%	6	36	8.32	7.83	1007	.0373	.957	.680
"	25%	6	36	8.32	7.88	1009	.0422	.937	.696
"	25%	6	36	8.32	7.84	1009	.0469	.938	.709
"	25%	6	36	8.32	7.88	1010	.0523	.918	.723
"	25%	6	36	8.32	7.88	1011	.0581	.909	.735
"	25%	6	36	8.32	7.87	1011	.0637	.911	.745

12" D Dump Combustor Data

Test	Flame Holder	D_2	L_c (inches)	D^*	$\dot{W}_a$ (#/sec)	T_{t2} (°R)	f/a	η_c	P_{t5}/P_{t2}
Fuel Inj.	25%	6	36	8.32	7.91	1017	.0322	.956	.652
(Pintel)	25%	6	36	8.32	7.90	1018	.0367	.961	.673
"	25%	6	36	8.32	7.99	1018	.0411	.931	.688
"	25%	6	36	8.32	7.90	1018	.0468	.942	.706
"	25%	6	36	8.32	7.99	1018	.0511	.914	.714
"	25%	6	36	8.32	7.98	1010	.0563	.899	.723
"	25%	6	36	8.32	7.95	1010	.0632	.885	.732
Pressure	0	6	36	8.32	9.89	1022	.0252	.774	.743
Pressure	0	6	36	8.32	9.83	1024	.0312	.789	.772
Pressure	0	6	36	8.32	9.83	1025	.0365	.772	.785
Pressure	0	6	36	8.32	9.76	1027	.0416	.837	.805
Pressure	0	6	36	8.32	9.84	1028	.0462	.803	.807
Pressure	0	6	36	8.32	9.85	1028	.0513	.794	.819
Pressure	0	6	36	8.32	9.80	1029	.0566	.803	.825
Pressure	0	6	36	8.32	9.76	1029	.0620	.810	.829
Pressure	0	6	36	8.32	4.76	1023	.0281	.823	.754
Pressure	0	6	36	8.32	4.80	1024	.0317	.791	.763
Pressure	0	6	36	8.32	4.76	1026	.0382	.785	.786
Pressure	0	6	36	8.32	4.80	1029	.0429	.835	.799
Pressure	0	6	36	8.32	4.83	1031	.0479	.824	.807
Pressure	0	6	36	8.32	4.80	1032	.0532	.817	.813
Pressure	0	6	36	8.32	4.78	1033	.0588	.809	.821
Pressure	0	6	36	8.32	4.77	1034	.0638	.794	.822

12" D Dump Combustor Data

Test	Flame Holder	D_2	L_c (inches)	D^*	$\dot{W}_a$ (#/sec)	T_{t2} (°R)	f/a	η_c	P_{t5}/P_{t2}
Pressure	25%	6	36	8.32	9.73	1005	.0261	.955	.629
Pressure	25%	6	36	8.32	9.81	1005	.0308	.941	.655
Pressure	25%	6	36	8.32	9.67	1005	.0366	.942	.679
Pressure	25%	6	36	8.32	9.59	1004	.0421	.935	.695
Pressure	25%	6	36	8.32	9.63	998	.0472	.918	.713
Pressure	25%	6	36	8.32	9.61	999	.0519	.900	.720
Pressure	25%	6	36	8.32	9.66	999	.0571	.882	.730
Pressure	25%	6	36	8.32	9.61	1000	.0623	.883	.738
Pressure	25%	6	36	8.32	5.10	1012	.0267	.882	.622
Pressure	25%	6	36	8.32	5.09	1013	.0299	.922	.647
Pressure	25%	6	36	8.32	5.09	1014	.0350	.911	.669
Pressure	25%	6	36	8.32	5.09	1013	.0388	.908	.684
Pressure	25%	6	36	8.32	5.11	1014	.0444	.899	.702
Pressure	25%	6	36	8.32	5.07	1015	.0502	.891	.718
Pressure	25%	6	36	8.32	5.14	1020	.0533	.834	.711
Pressure	25%	6	36	8.32	5.11	1020	.0595	.830	.724
Pressure	0	6	36	8.32	9.78	1003	.0262	.743	.727
(Pintel)	0	6	36	8.32	9.72	1005	.0312	.779	.756
"	0	6	36	8.32	9.74	1007	.0360	.815	.775
"	0	6	36	8.32	9.72	1008	.0412	.859	.793
"	0	6	36	8.32	9.81	1010	.0459	.857	.804
"	0	6	36	8.32	9.67	1011	.0519	.871	.815
"	0	6	36	8.32	9.73	1012	.0567	.861	.826
"	0	6	36	8.32	9.68	1014	.0618	.851	.825

12" D Dump Combustor Data

Test	Flame Holder	D_2	L_c (inches)	D^* (inches)	$\dot{W}_a$ (#/sec)	T_{t2} (°R)	f/a	η_c	P_{t5}/P_{t2}
Pressure	0	6	36	8.32	4.87	1012	.0271	.708	.728
(Pintel)	0	6	36	8.32	4.82	1013	.0309	.720	.744
"	0	6	36	8.32	4.88	1013	.0367	.725	.765
"	0	6	36	8.32	4.87	1015	.0423	.732	.780
"	0	6	36	8.32	4.86	1017	.0476	.748	.792
"	0	6	36	8.32	4.84	1018	.0524	.773	.805
"	0	6	36	8.32	4.85	1020	.0568	.769	.809
"	0	6	36	8.32	4.89	1021	.0617	.791	.826
Pressure	25%	6	36	8.32	9.96	1003	.0303	.976	.648
(Pintel)	25%	6	36	8.32	10.03	1004	.0348	.965	.670
"	25%	6	36	8.32	9.92	1005	.0403	.974	.690
"	25%	6	36	8.32	10.09	1006	.0448	.932	.706
"	25%	6	36	8.32	9.99	1007	.0498	.935	.712
"	25%	6	36	8.32	9.97	1020	.0551	.903	.717
"	25%	6	36	8.32	9.94	1021	.0599	.894	.724
Pressure	25%	6	36	8.32	4.88	1011	.0316	.929	.651
(Pintel)	25%	6	36	8.32	4.88	1012	.0369	.931	.675
"	25%	6	36	8.32	4.93	1012	.0411	.902	.687
"	25%	6	36	8.32	4.88	1012	.0475	.904	.705
"	25%	6	36	8.32	4.88	1013	.0520	.903	.718
"	25%	6	36	8.32	4.87	1013	.0573	.883	.724
"	25%	6	36	8.32	4.87	1014	.0618	.870	.733

12" D Dump Combustor Data

Test	Flame Holder	D_2	L_c (inches)	D^*	$\dot{W}_a$ (#/sec)	T_{t2} (°R)	f/a	η_c	P_{t5}/P_{t2}
RJ-5	0	6	36	8.32	7.81	998	.0233	.785	.723
RJ-5	0	6	36	8.32	7.83	1000	.0290	.771	.751
RJ-5	0	6	36	8.32	7.81	1002	.0336	.771	.768
RJ-5	0	6	36	8.32	7.83	1005	.0390	.758	.784
RJ-5	0	6	36	8.32	7.80	1007	.0439	.765	.796
RJ-5	0	6	36	8.32	7.80	1010	.0491	.759	.803
RJ-5	0	6	36	8.32	7.83	1012	.0549	.746	.810
RJ-5	0	6	36	8.32	7.80	1012	.0603	.743	.814
RJ-5	0	6	36	8.32	8.08	746	.0229	.669	.737
RJ-5	0	6	36	8.32	8.12	747	.0278	.665	.760
RJ-5	0	6	36	8.32	8.06	748	.0325	.683	.778
RJ-5	0	6	36	8.32	8.14	750	.0369	.681	.788
RJ-5	0	6	36	8.32	8.08	752	.0421	.701	.801
RJ-5	0	6	36	8.32	8.07	754	.0476	.705	.807
RJ-5	0	6	36	8.32	8.17	757	.0520	.643	.798
RJ-5	0	6	36	8.32	8.09	758	.0580	.615	.806
Temp.	0	6	36	8.32	7.87	760	.0261	.676	.751
Temp.	0	6	36	8.32	7.88	761	.0321	.686	.774
Temp.	0	6	36	8.32	7.96	762	.0365	.777	.799
Temp.	0	6	36	8.32	7.91	763	.0418	.762	.811
Temp.	0	6	36	8.32	7.87	764	.0469	.745	.816
Temp.	0	6	36	8.32	7.89	765	.0524	.735	.820
Temp.	0	6	36	8.32	7.94	765	.0571	.727	.824
Temp.	0	6	36	8.32	7.96	766	.0621	.761	.829

12" D Dump Combustor Data

Test	Flame Holder	D_2	L_c (inches)	D^*	$\dot{W}_a$ (#/sec)	T_{t2} (°R)	f/a	η_c	P_{t5}/P_{t2}
Premix	0	6	54	8.32	7.80	1017	.0436	.755	.793
Premix	0	6	54	8.32	7.79	1012	.0485	.797	.802
Premix	0	6	54	8.32	7.81	1009	.0538	.871	.820
Premix	0	6	54	8.32	7.77	1004	.0594	.908	.837
Premix	0	6	54	8.32	7.81	998	.0645	.917	.847
Premix	0	6	54	8.32	7.95	952	.0702	.909	.849
Premix	0	6	36	8.32	7.78	996	.0400	.476	.724
Premix	0	6	36	8.32	7.72	992	.0452	.501	.755
Premix	0	6	36	8.32	7.74	988	.0506	.478	.756
Premix	0	6	36	8.32	7.74	982	.0565	.559	.775
Premix	0	6	36	8.32	7.78	979	.0617	.704	.804
Premix	0	6	36	8.32	7.78	974	.0669	.808	.817
Premix	0	6	36	8.32	7.77	968	.0748	.847	.832

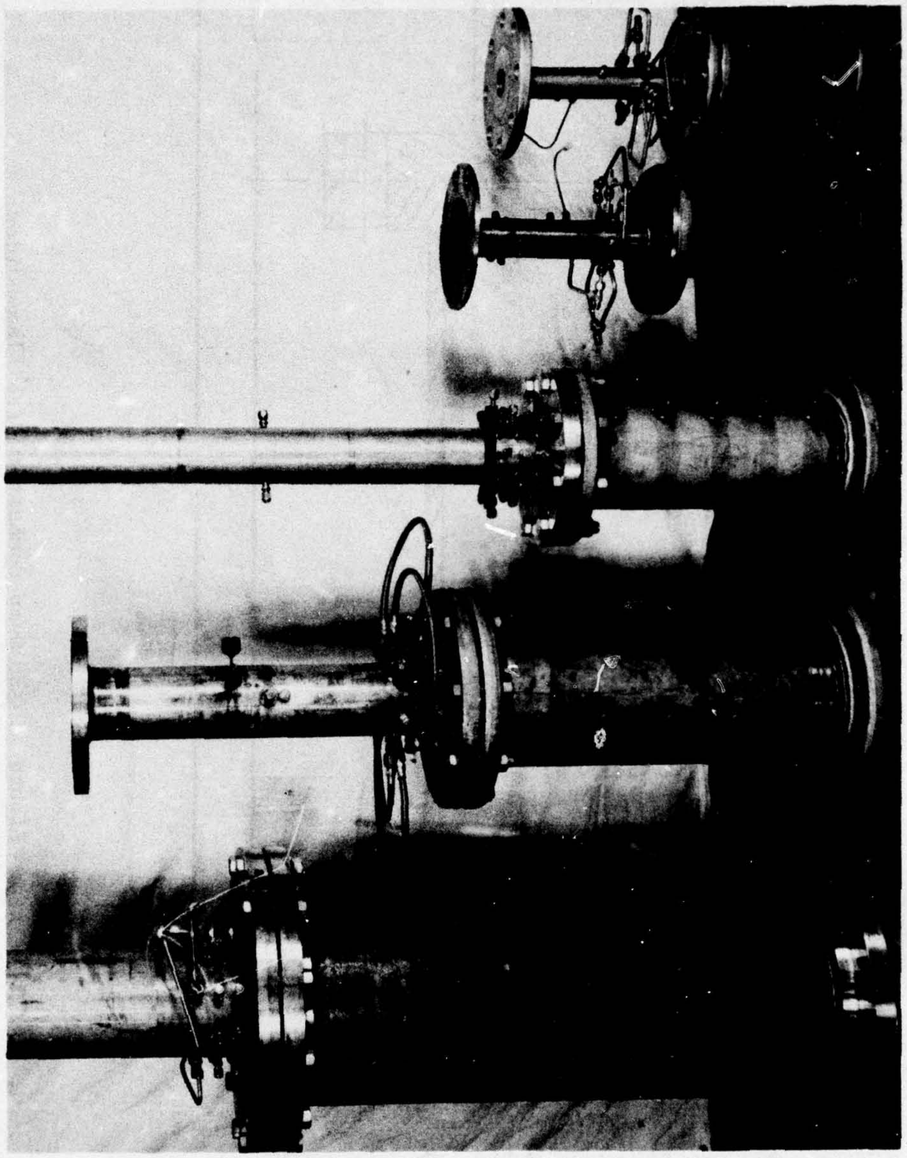

Figure 1. Scale Model Dump Combustors

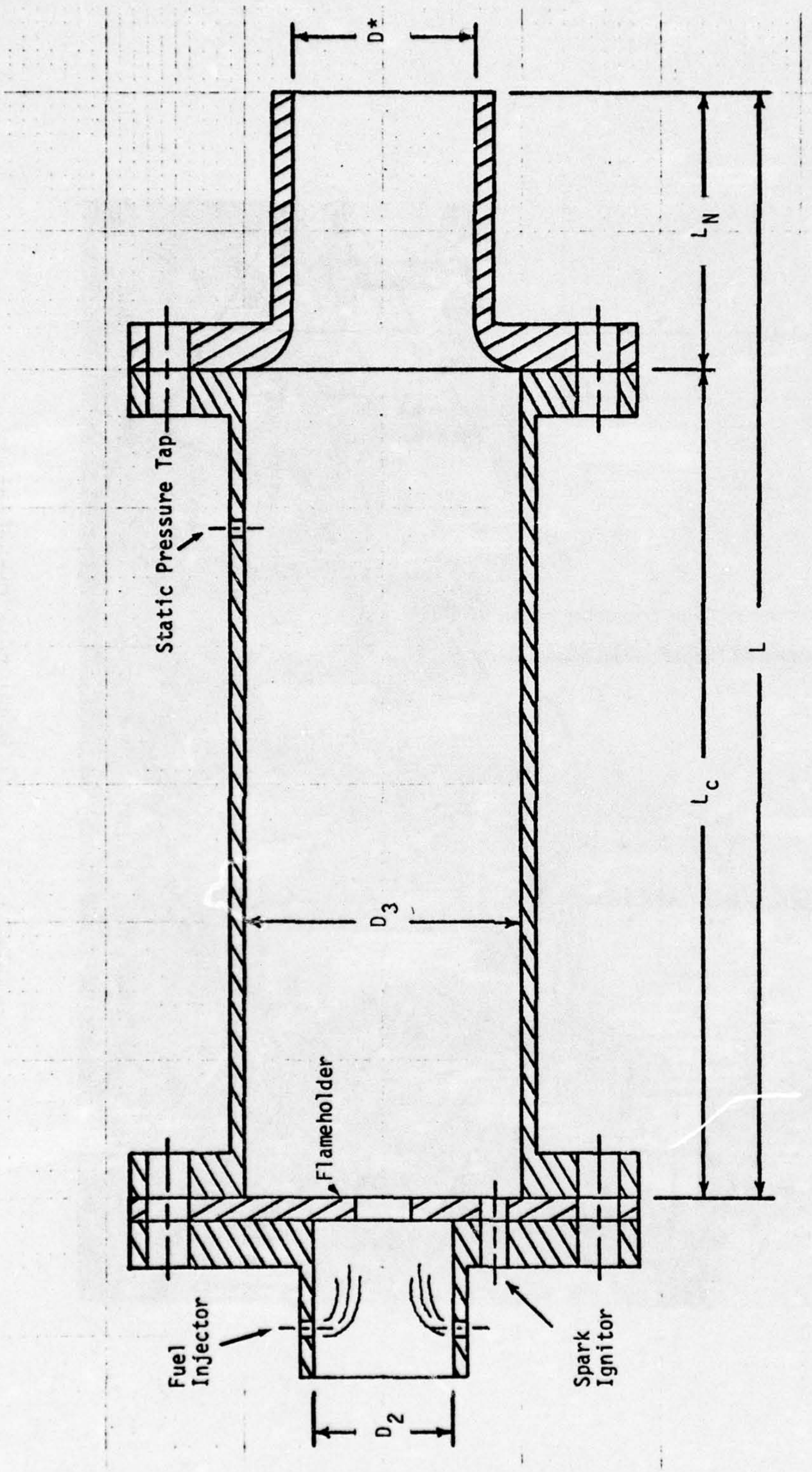

Figure 2. Dump Combustor With Flameholder

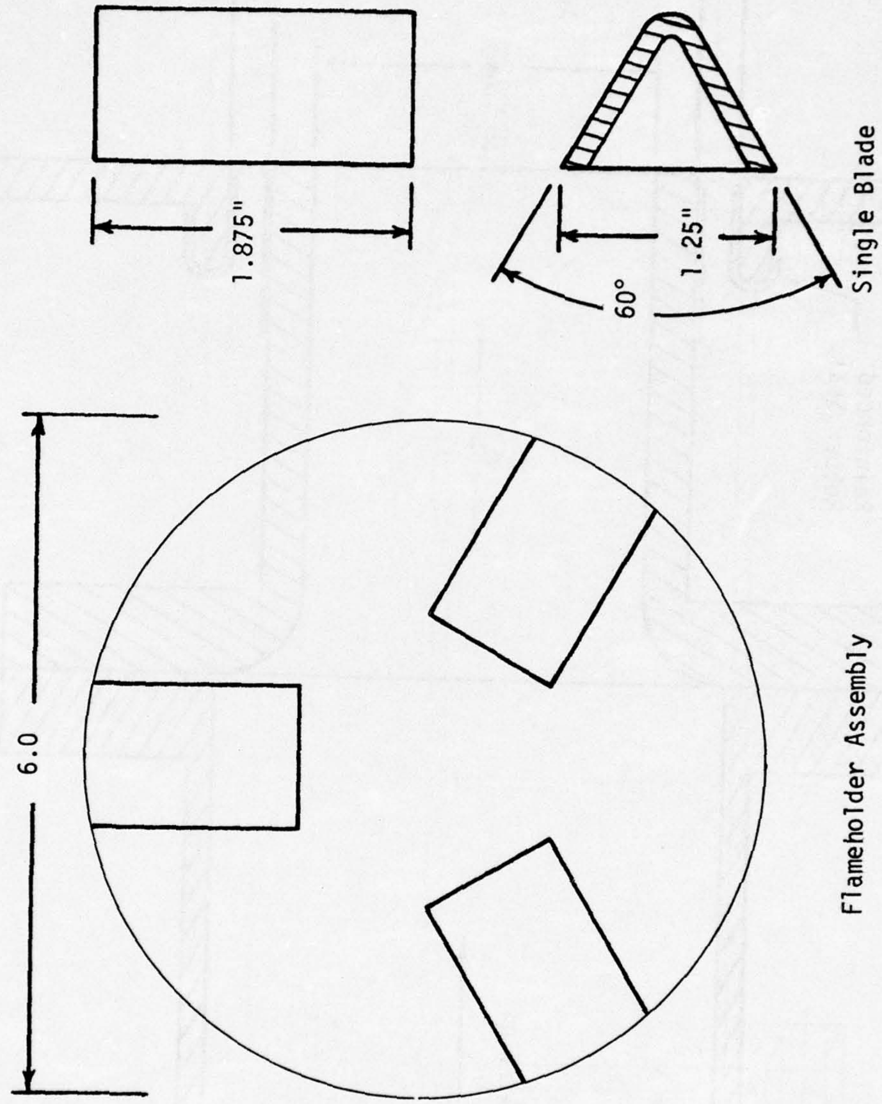

Figure 3. Flameholder Configuration

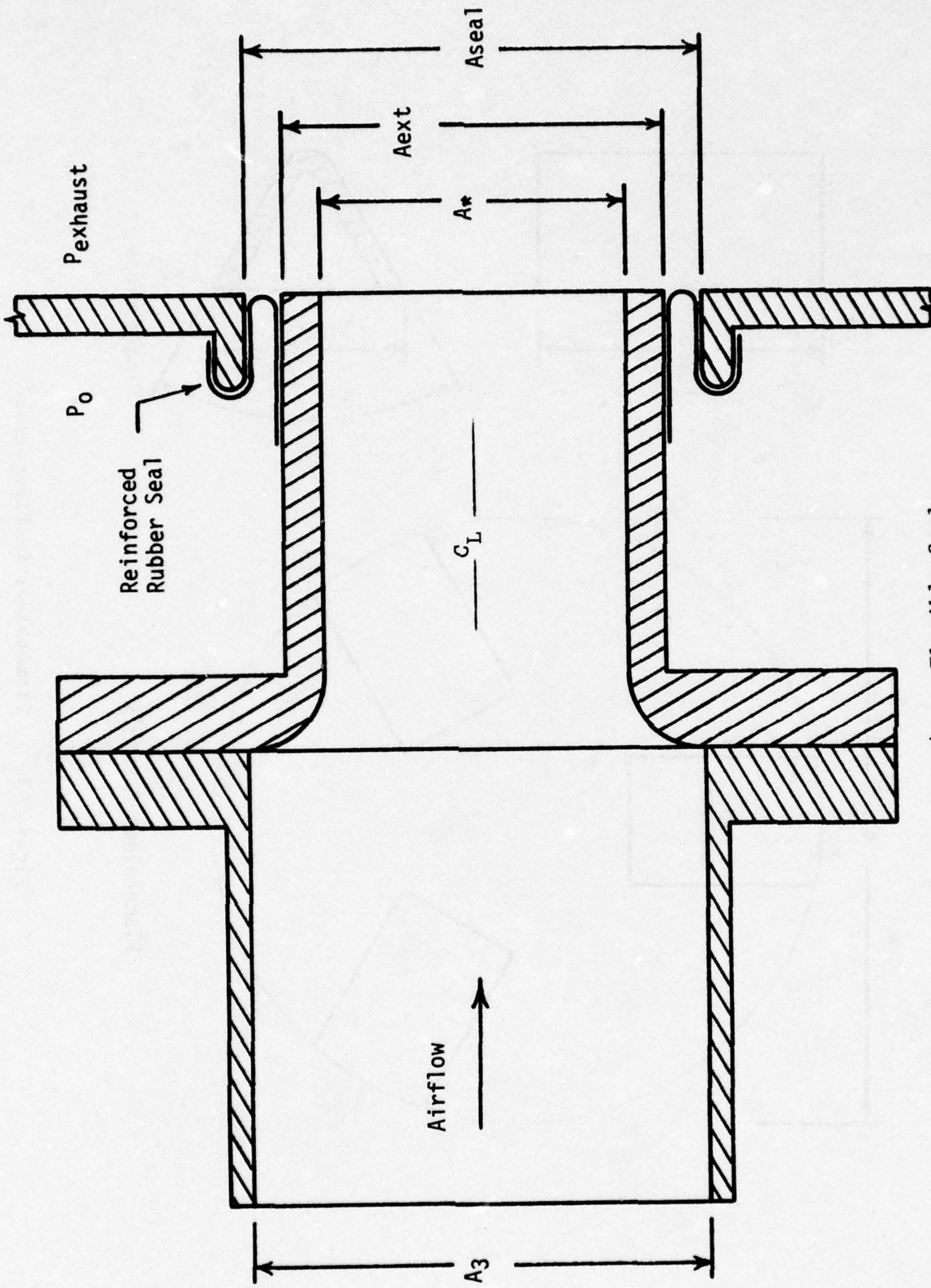

Figure 4. Flexible Seal

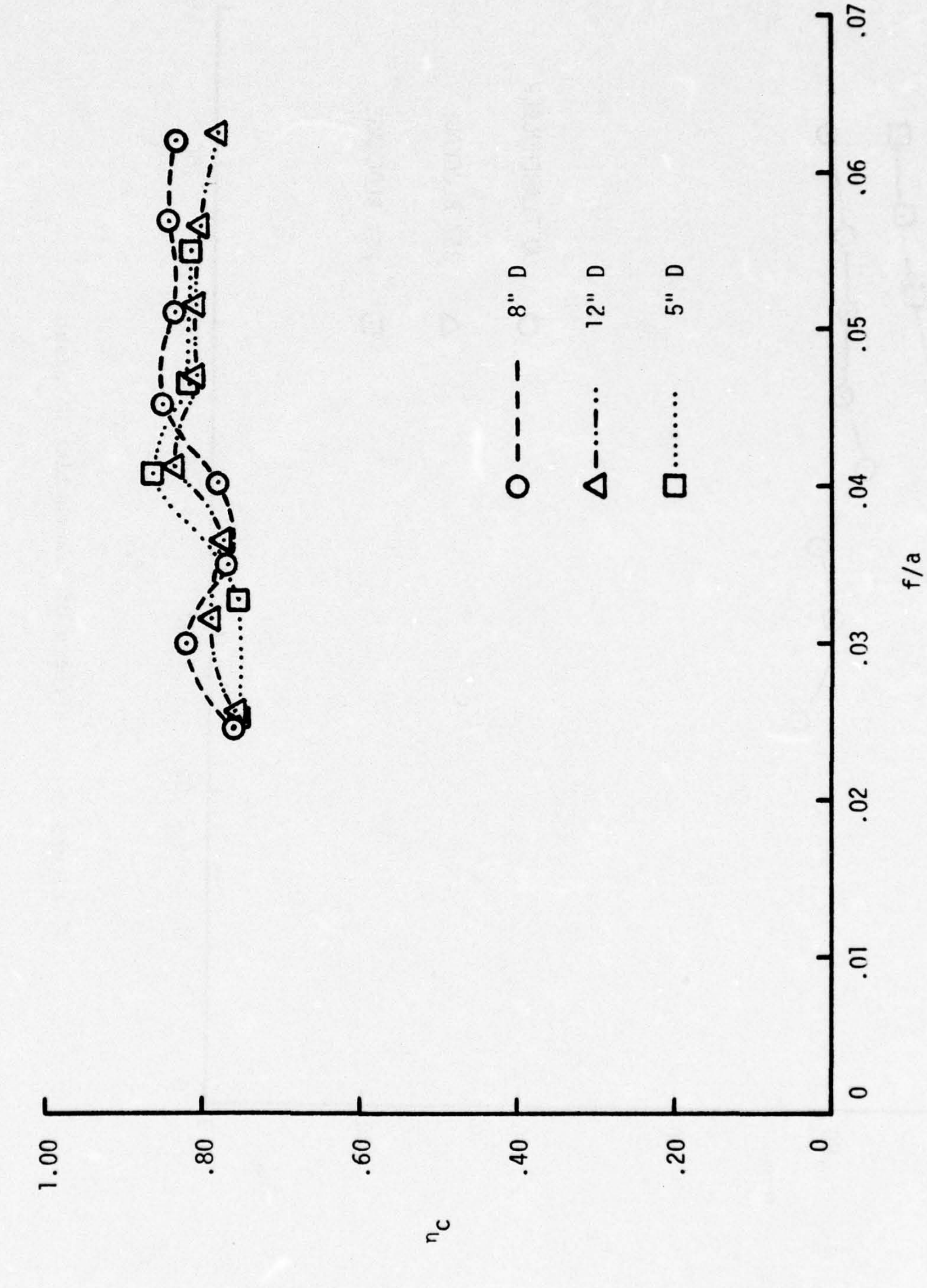

Figure 5. Pressure Scaling Tests

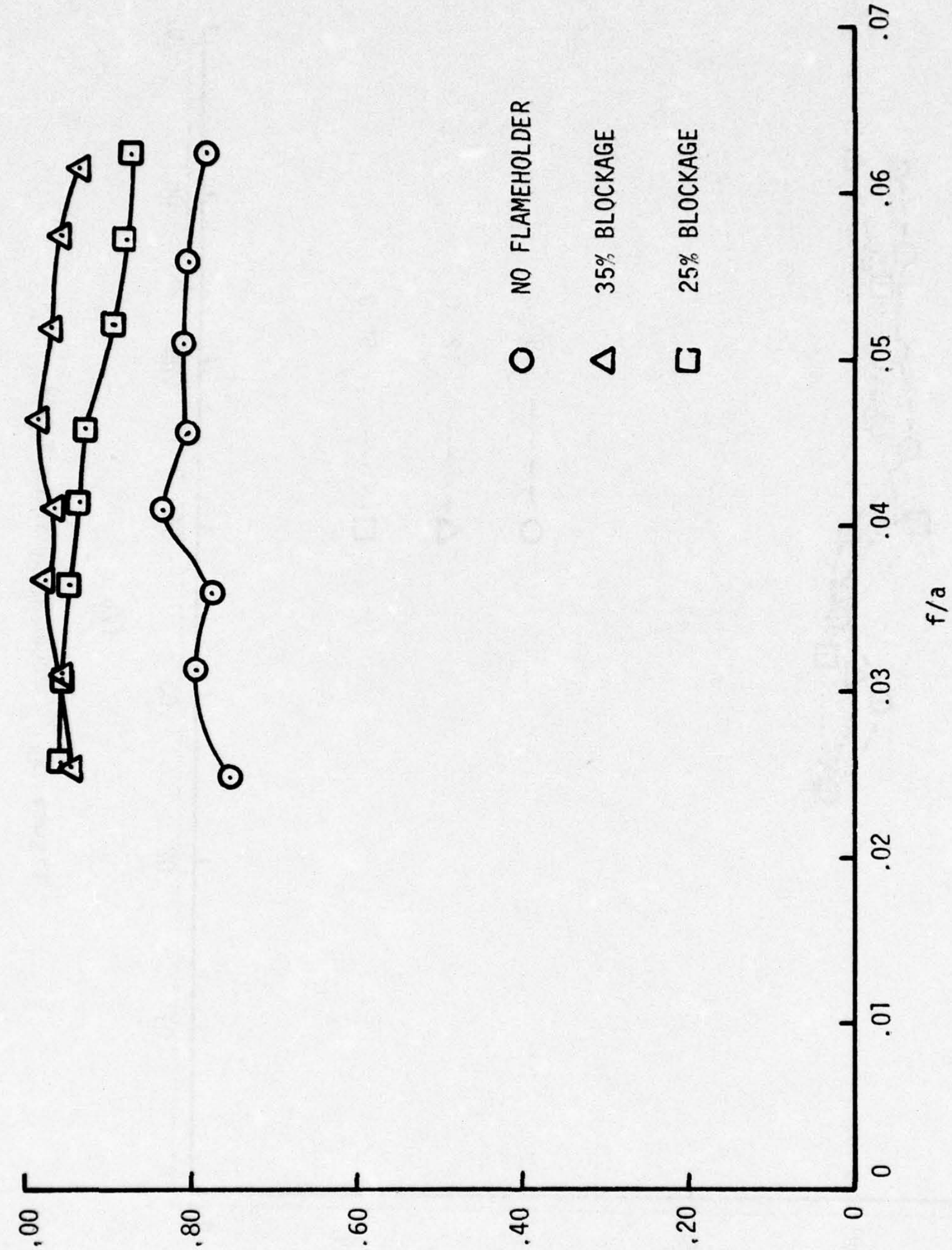

Figure 6. Effects of Flameholder Blockage

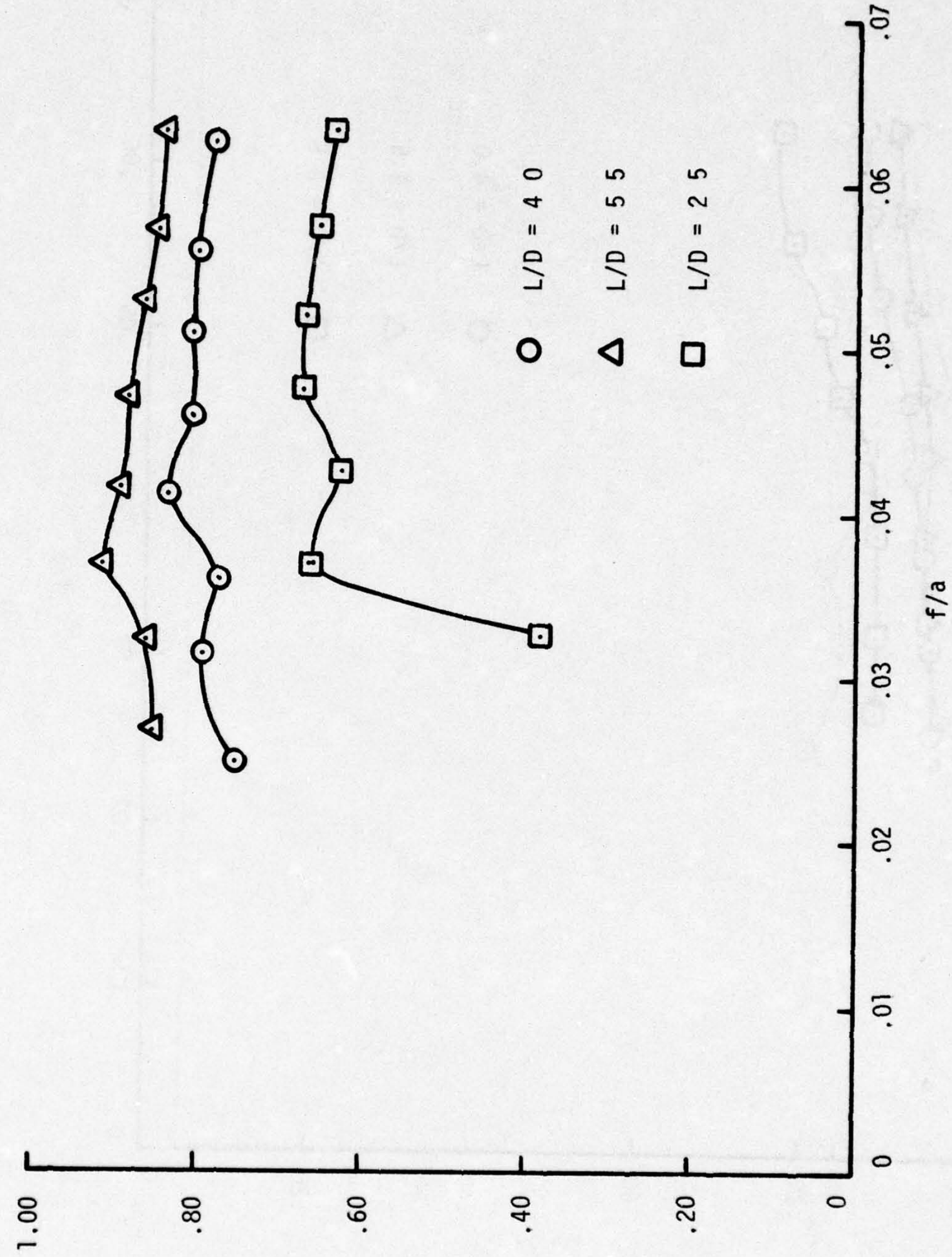

Figure 7. Effects of Combustor L/D: No Flameholder

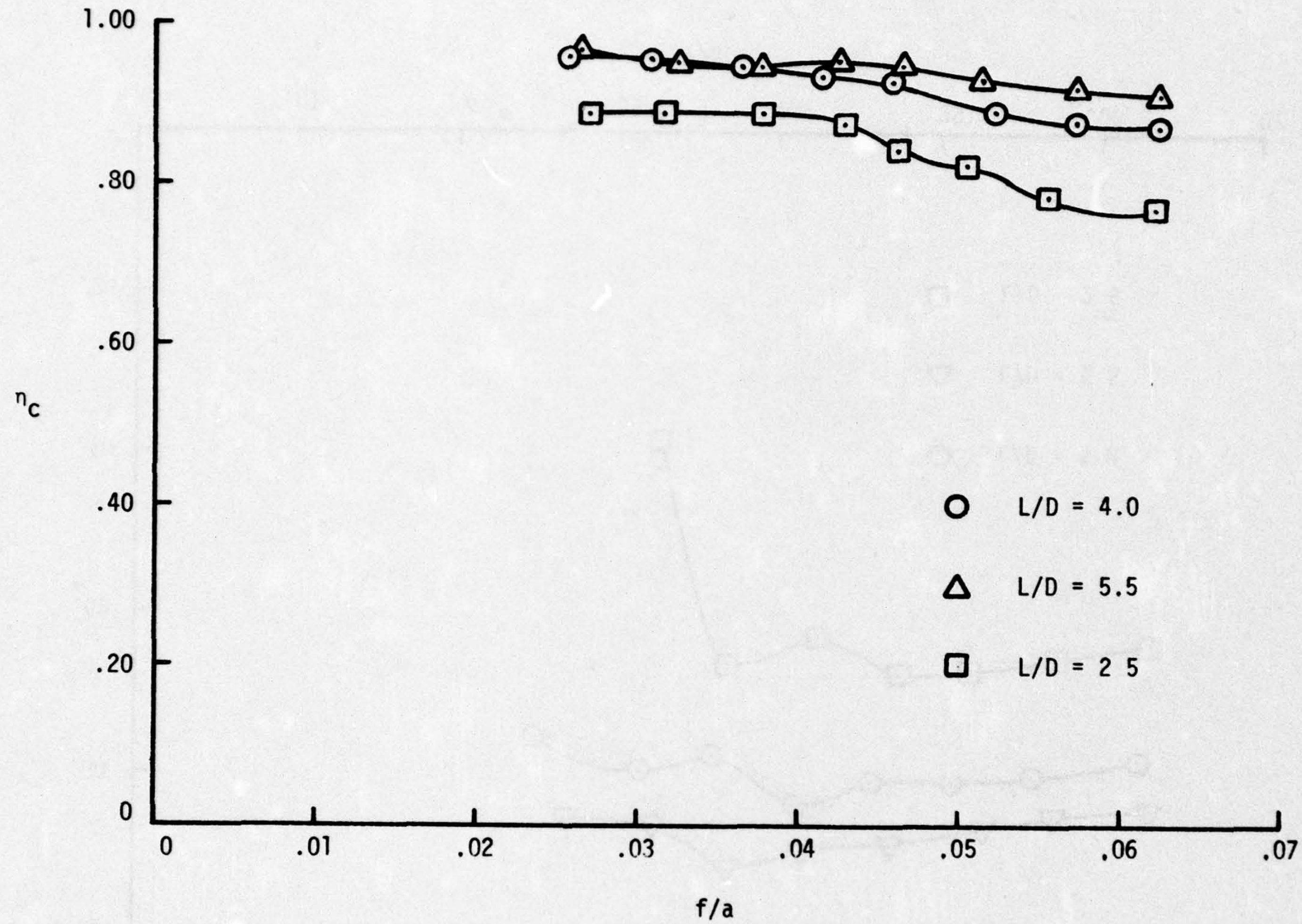

Figure 8. Effects of Combustor L/D: Flamehclder 25% Blockage

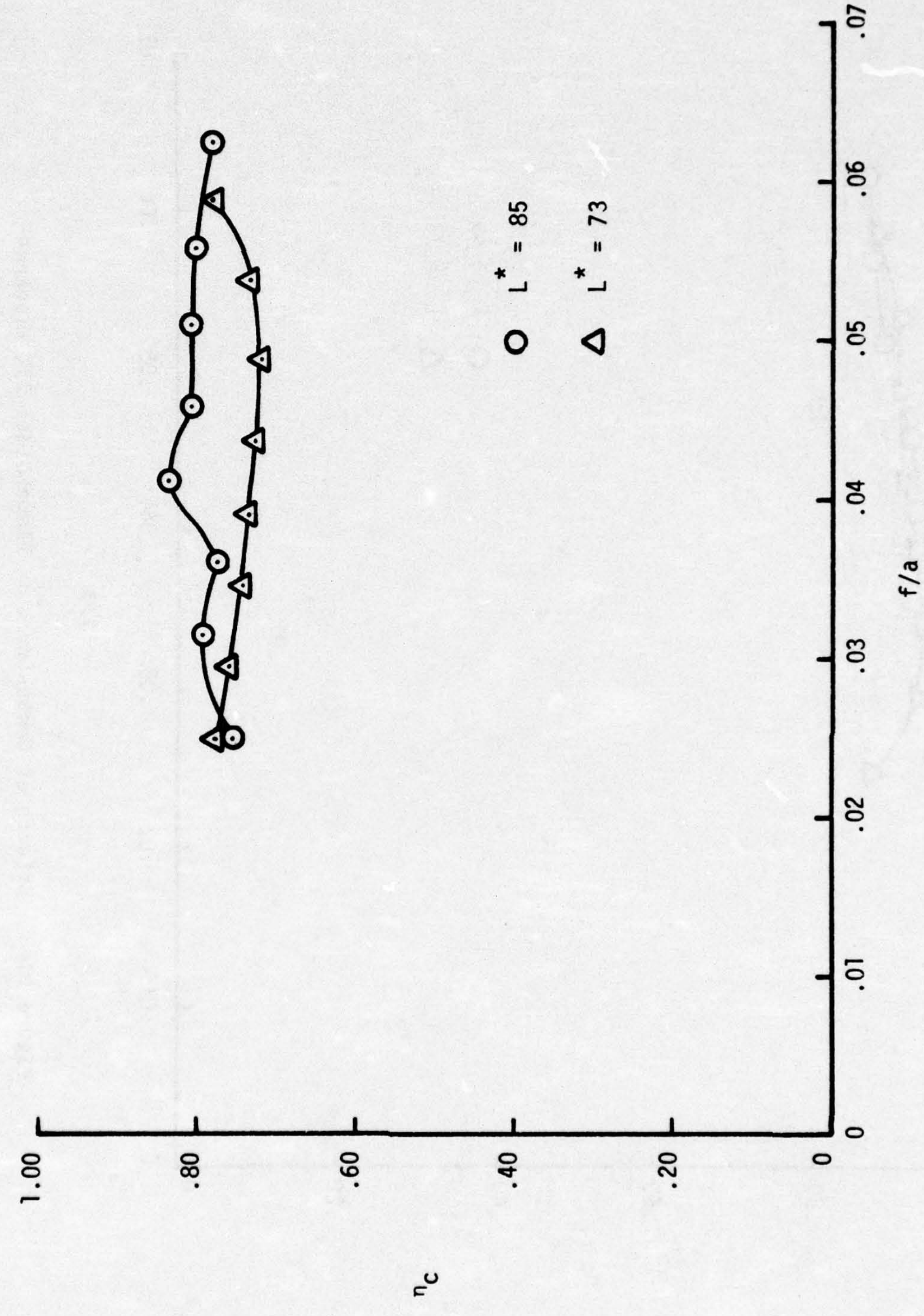

Figure 9. Effects of Combustor L^*: No Flameholder

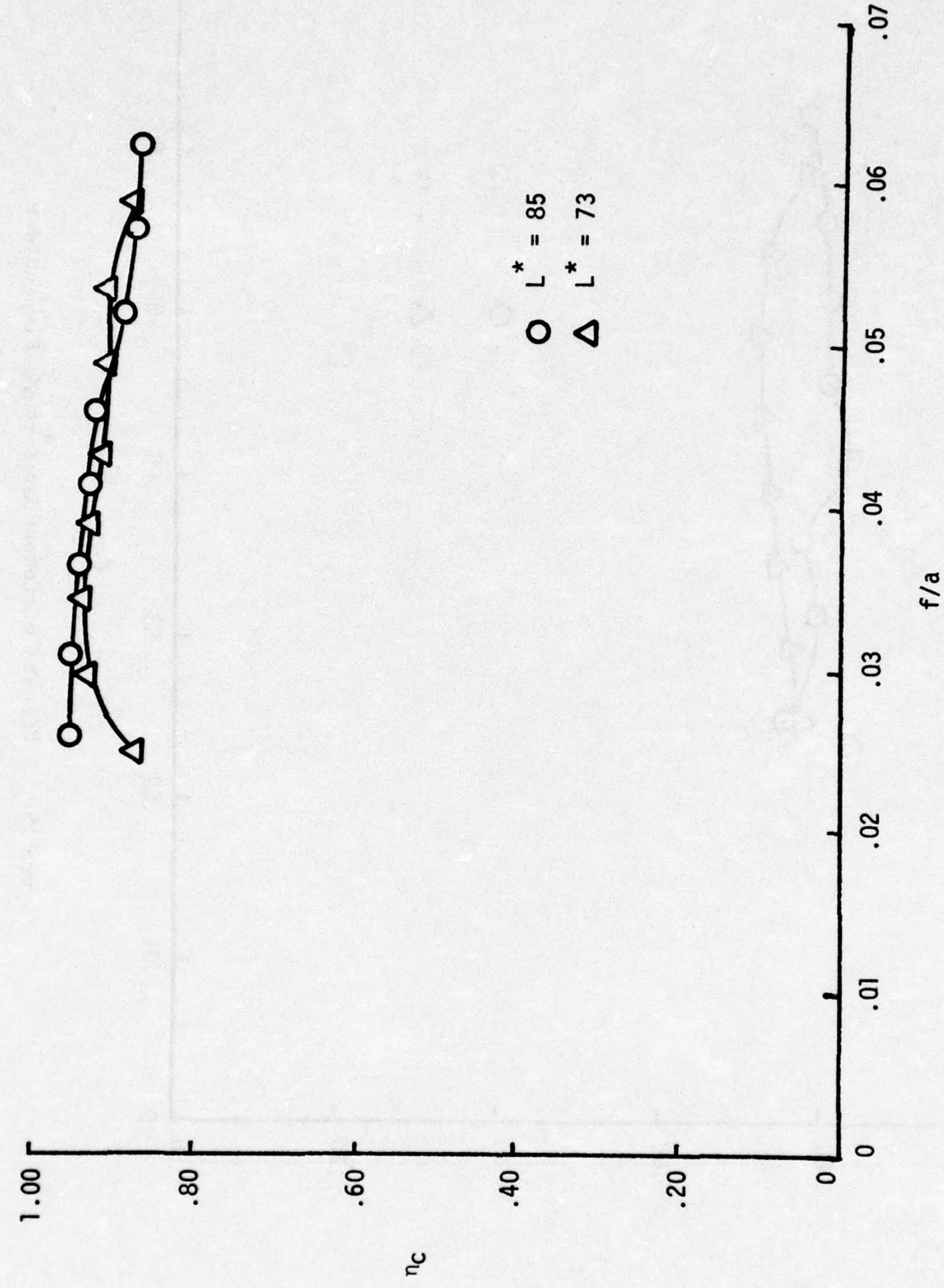

Figure 10. Effects of Combustor L^*: Flameholder 25% Blockage

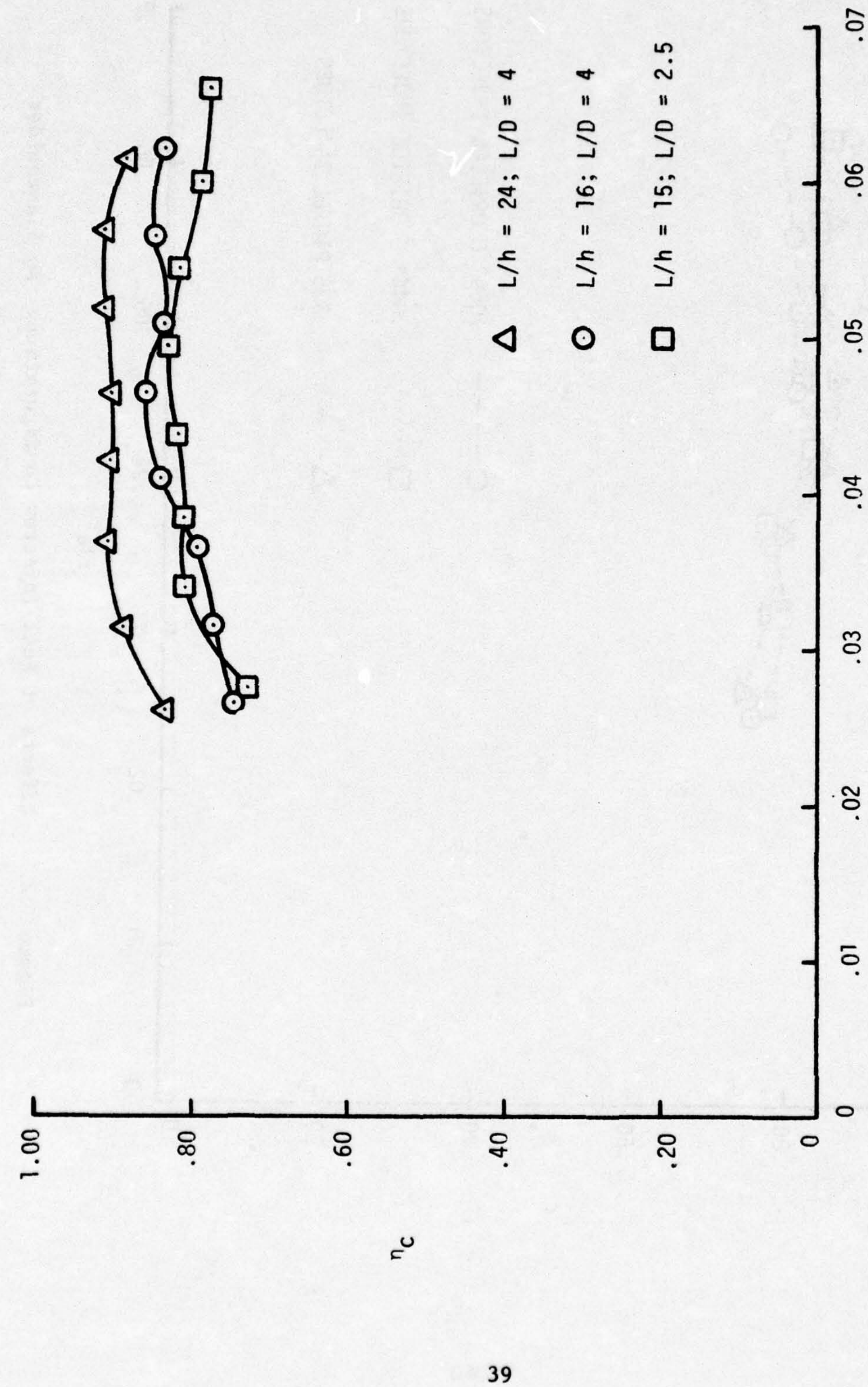

Figure 11. Effects of Combustor L/h

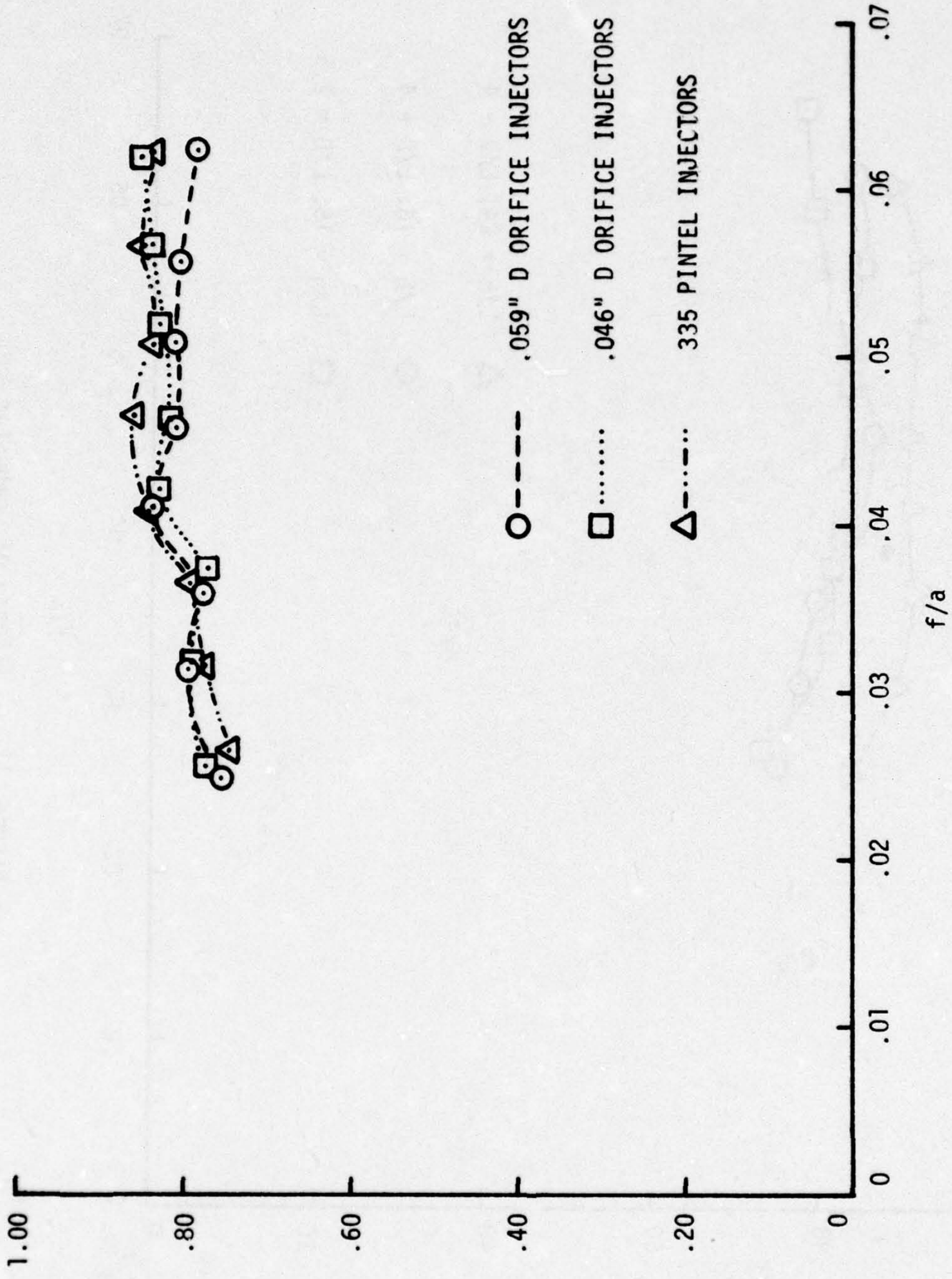

Figure 12. Effects of Fuel Injector Configuration: No Flameholder

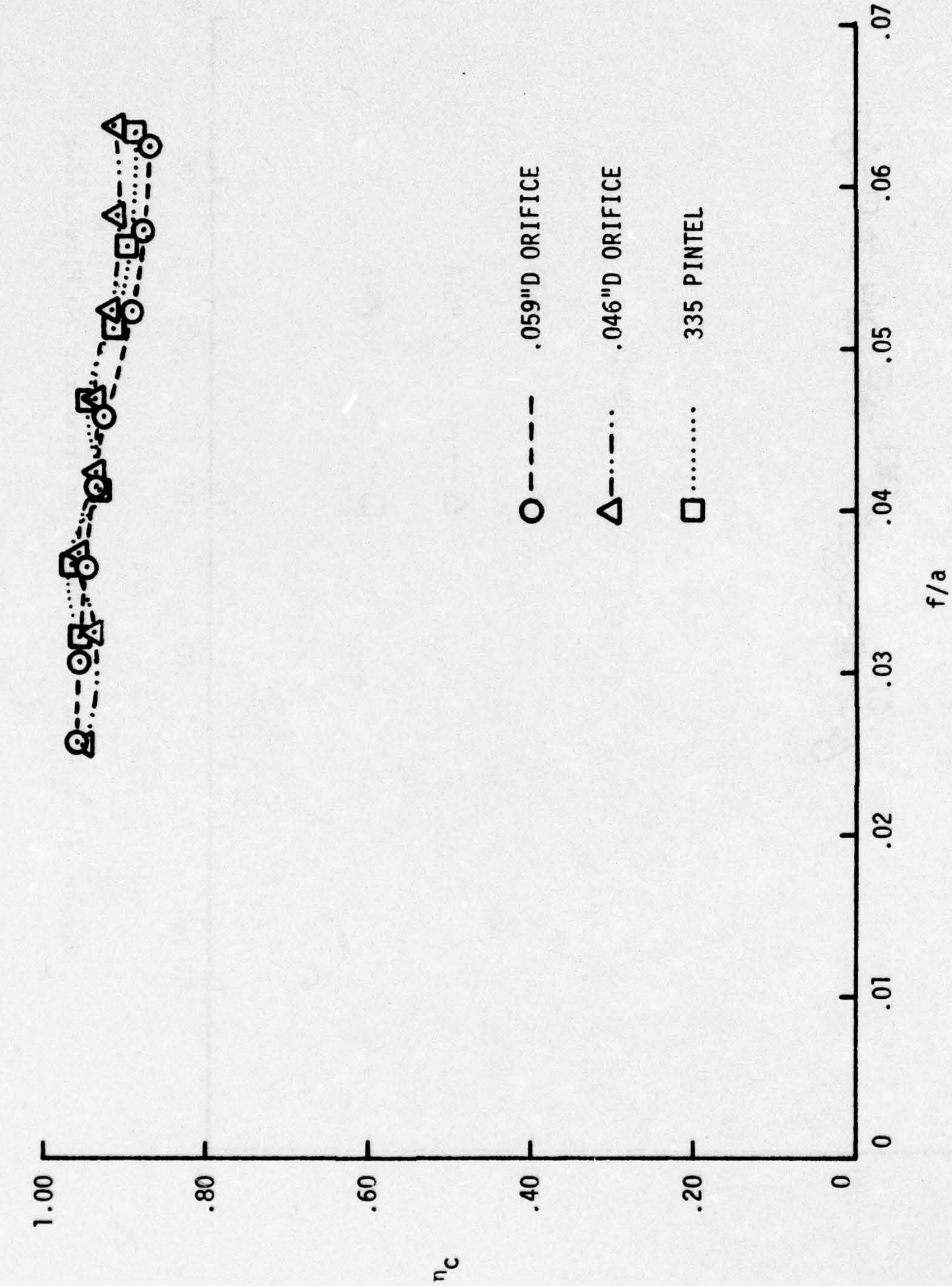

Figure 13. Effects of Fuel Injector Configuration: Flameholder 25% Blockage

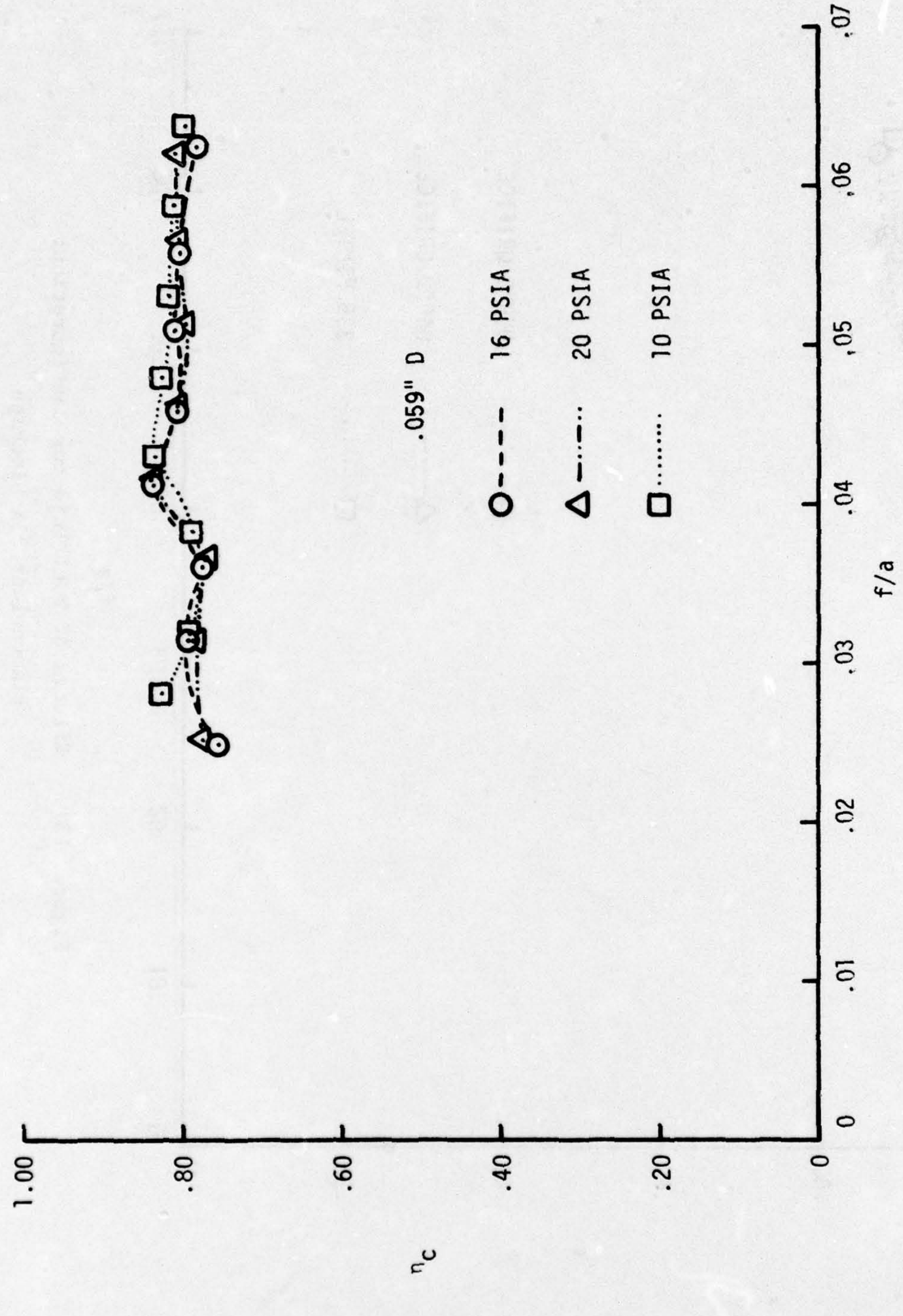

Figure 14. Effects of Combustor Pressure: No Flameholder

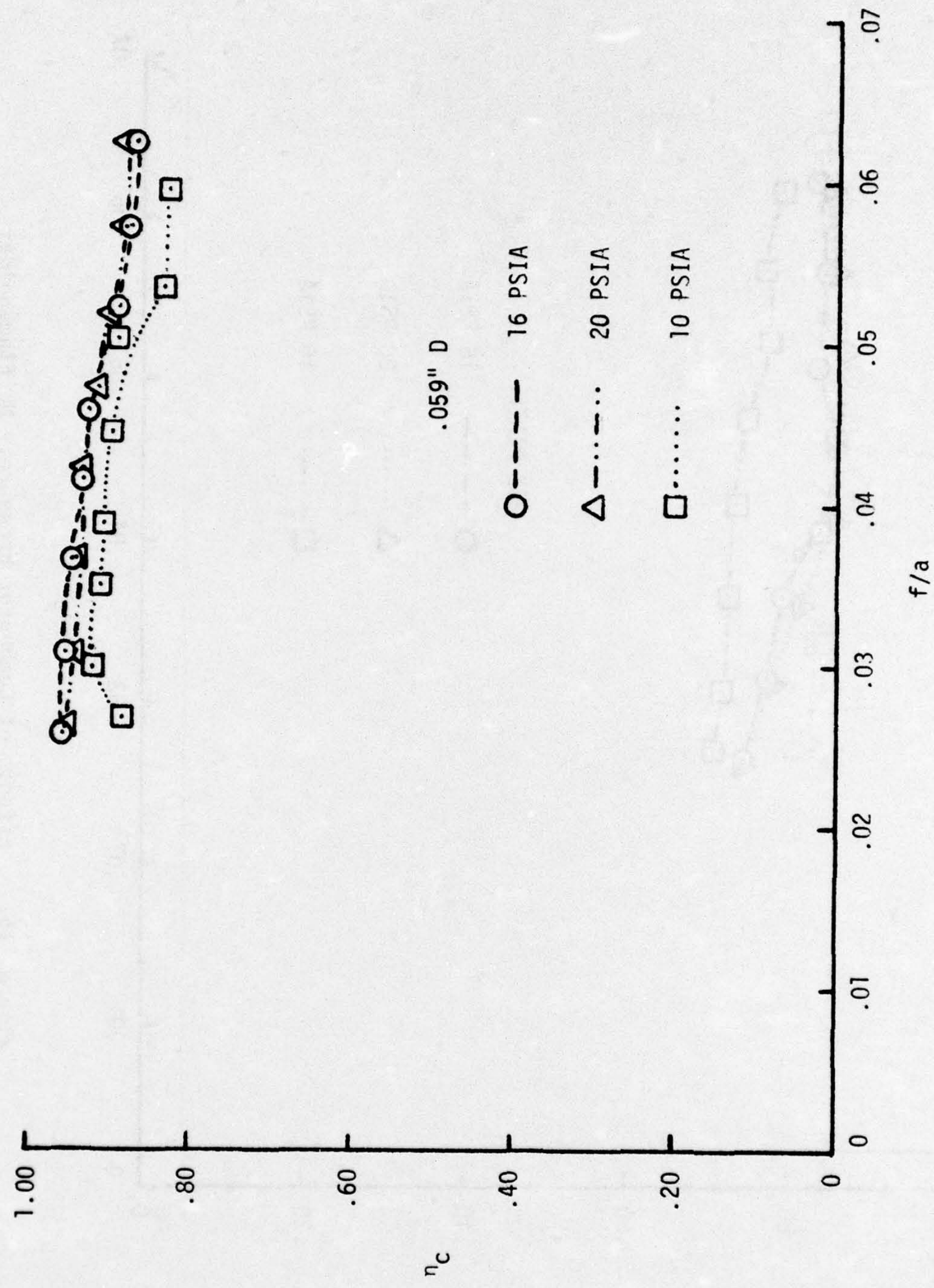

Figure 15. Effects of Combustor Pressure: Flameholder 25% Blockage

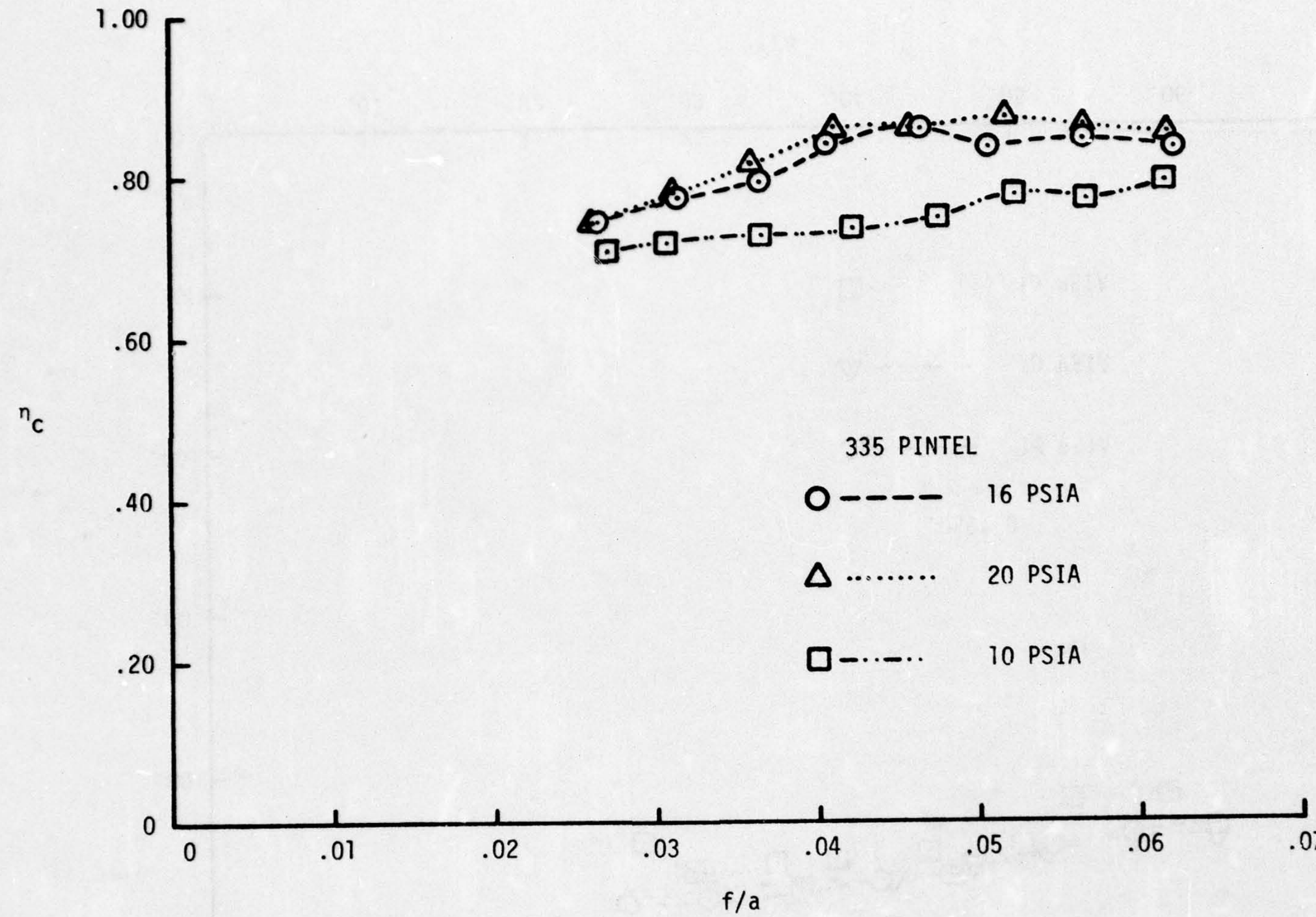

Figure 16. Effects of Combustor Pressure: No Flameholder

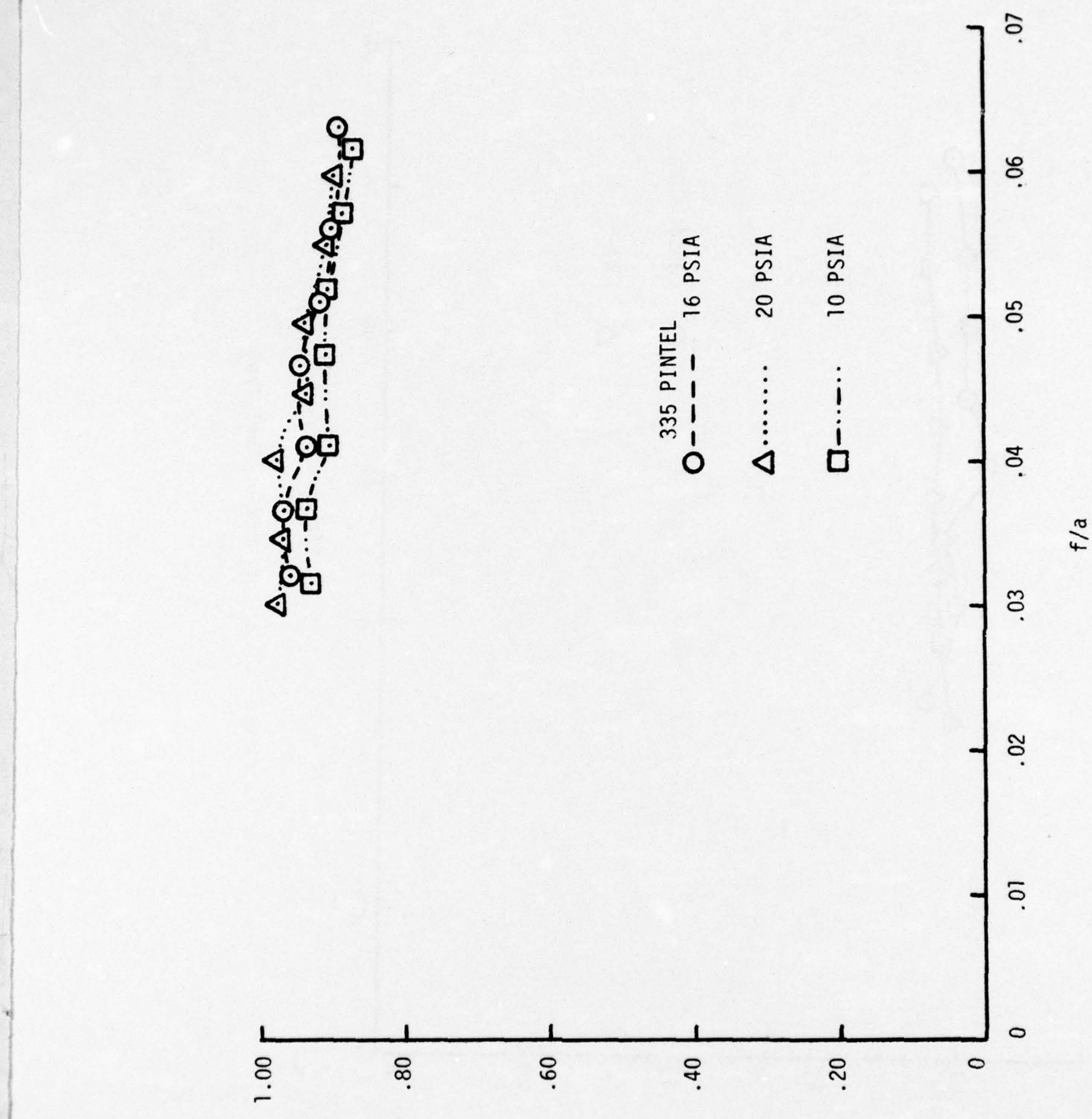

Figure 17. Effects of Combustor Pressure: Flameholder 25% Blockage

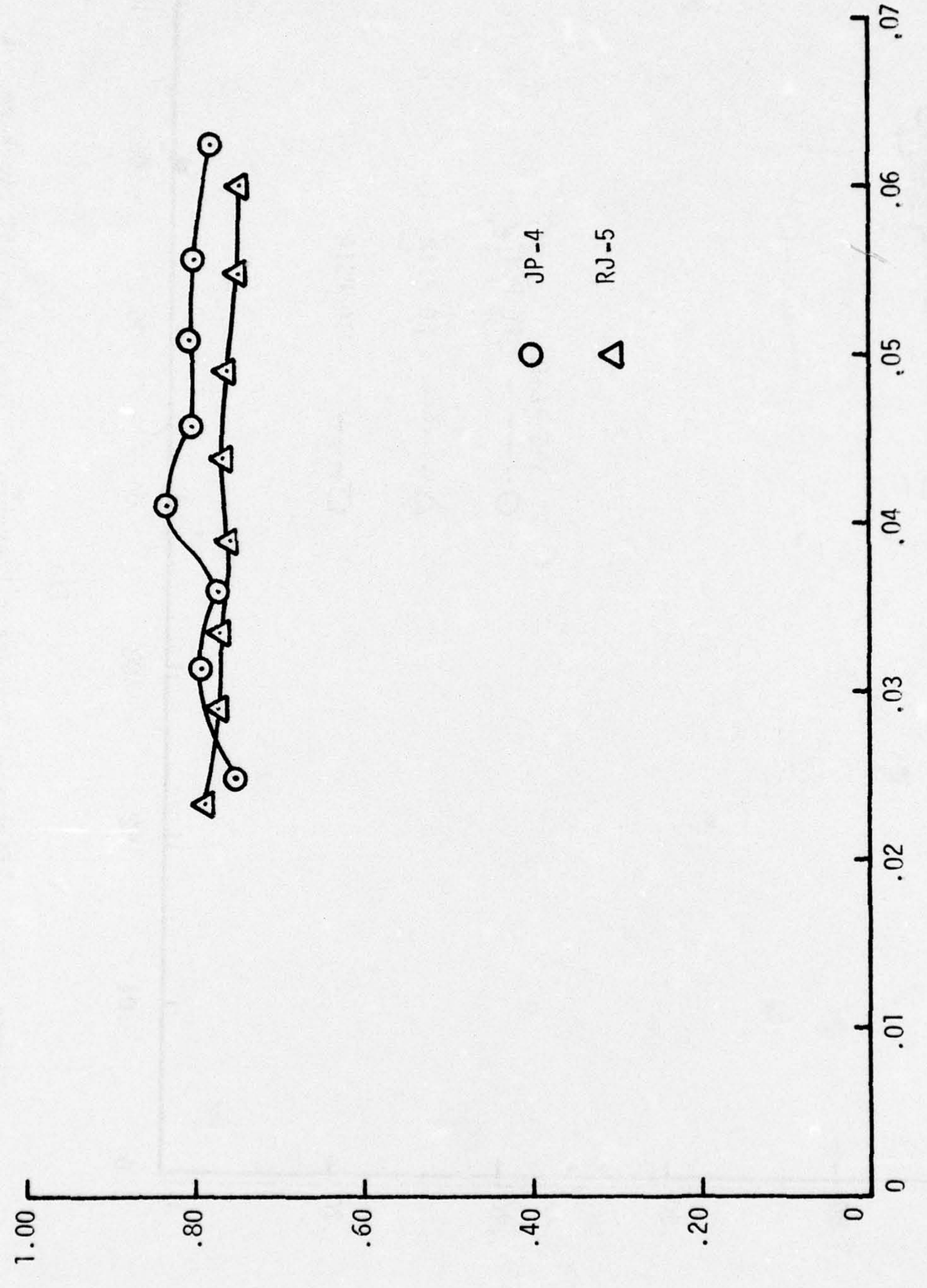

Figure 18. Effects of Fuel Type

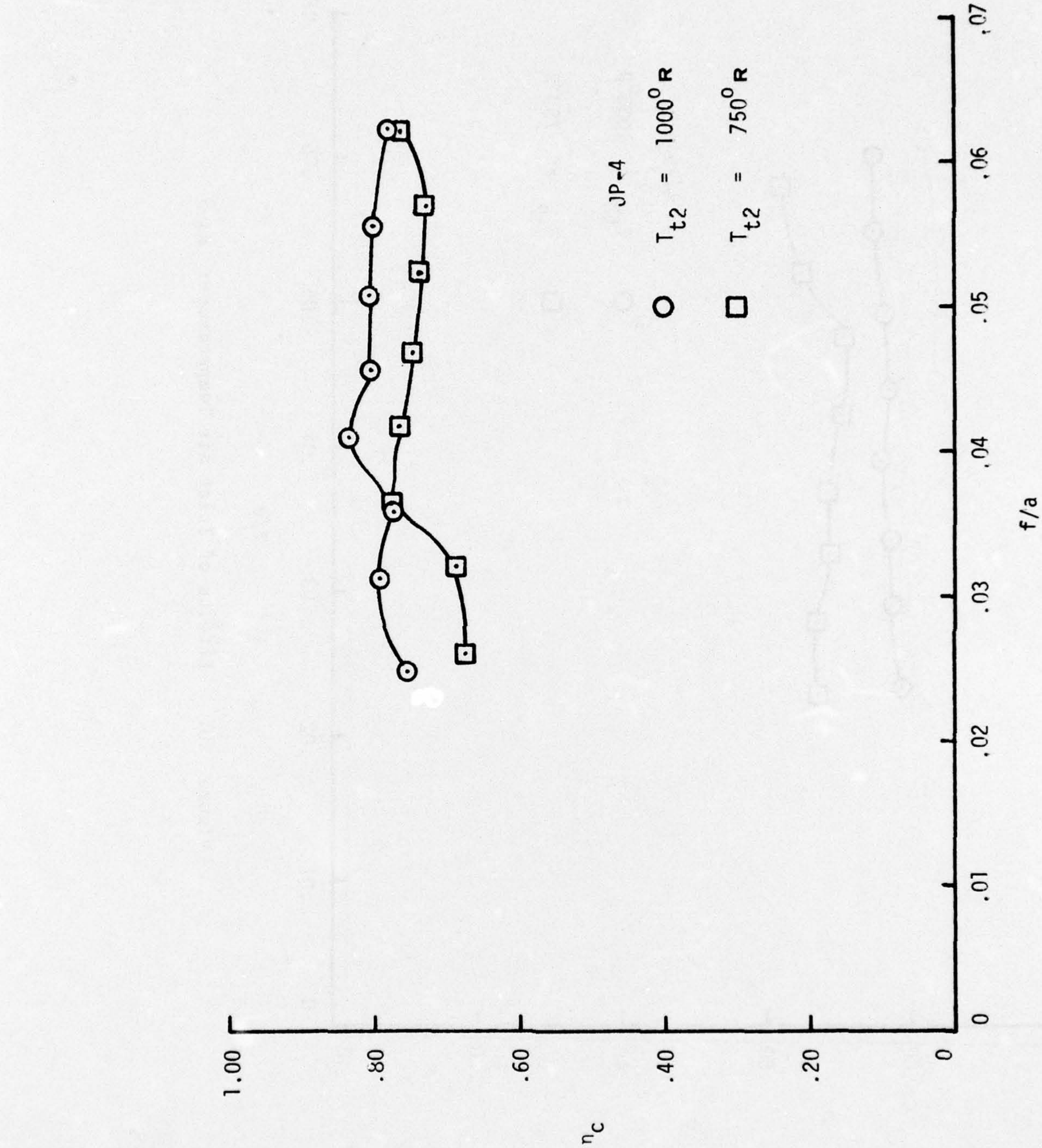

Figure 19. Effects of Inlet Air Temperature: JP-4

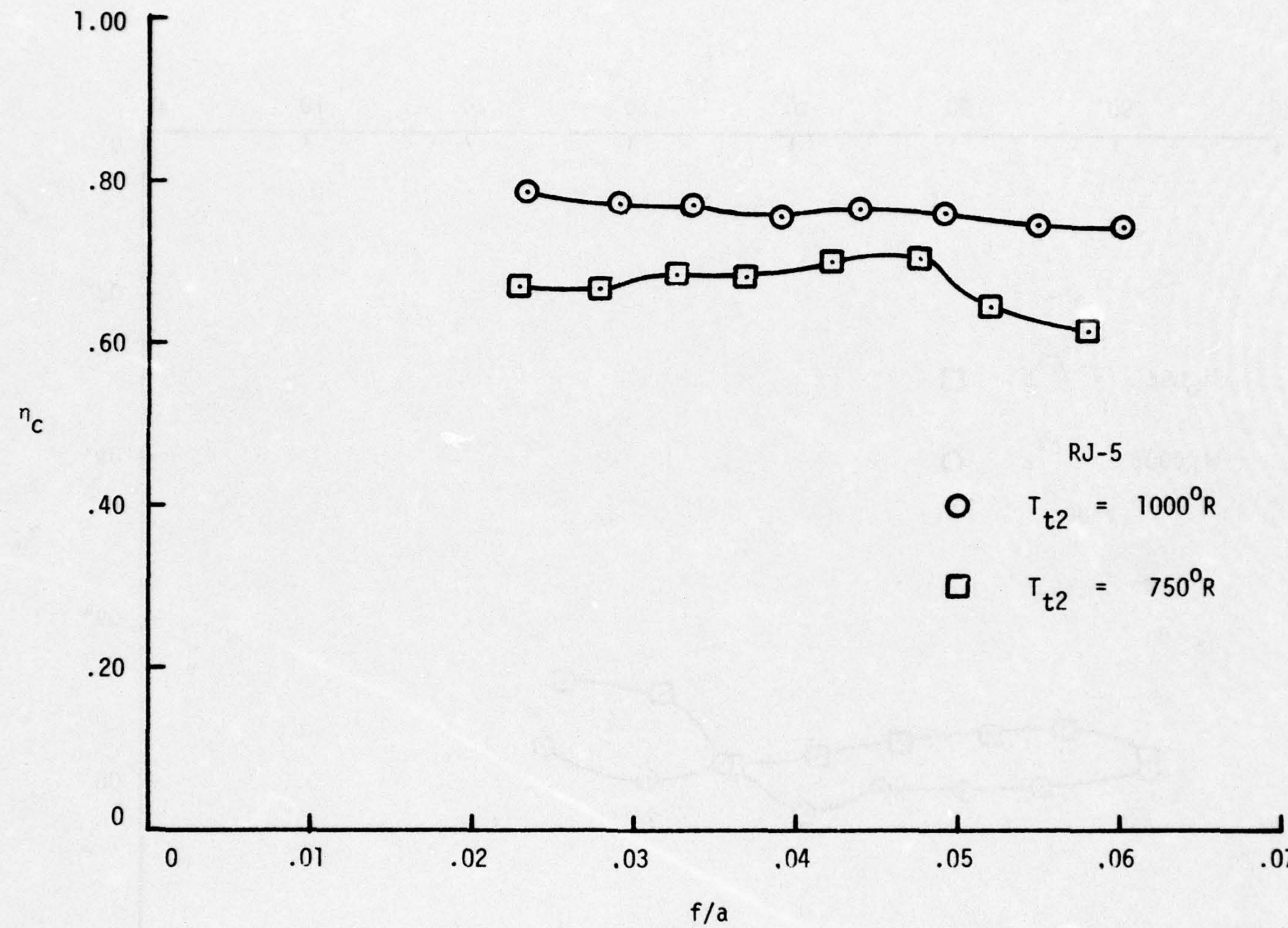

Figure 20. Effects of Inlet Air Temperature: RJ-5

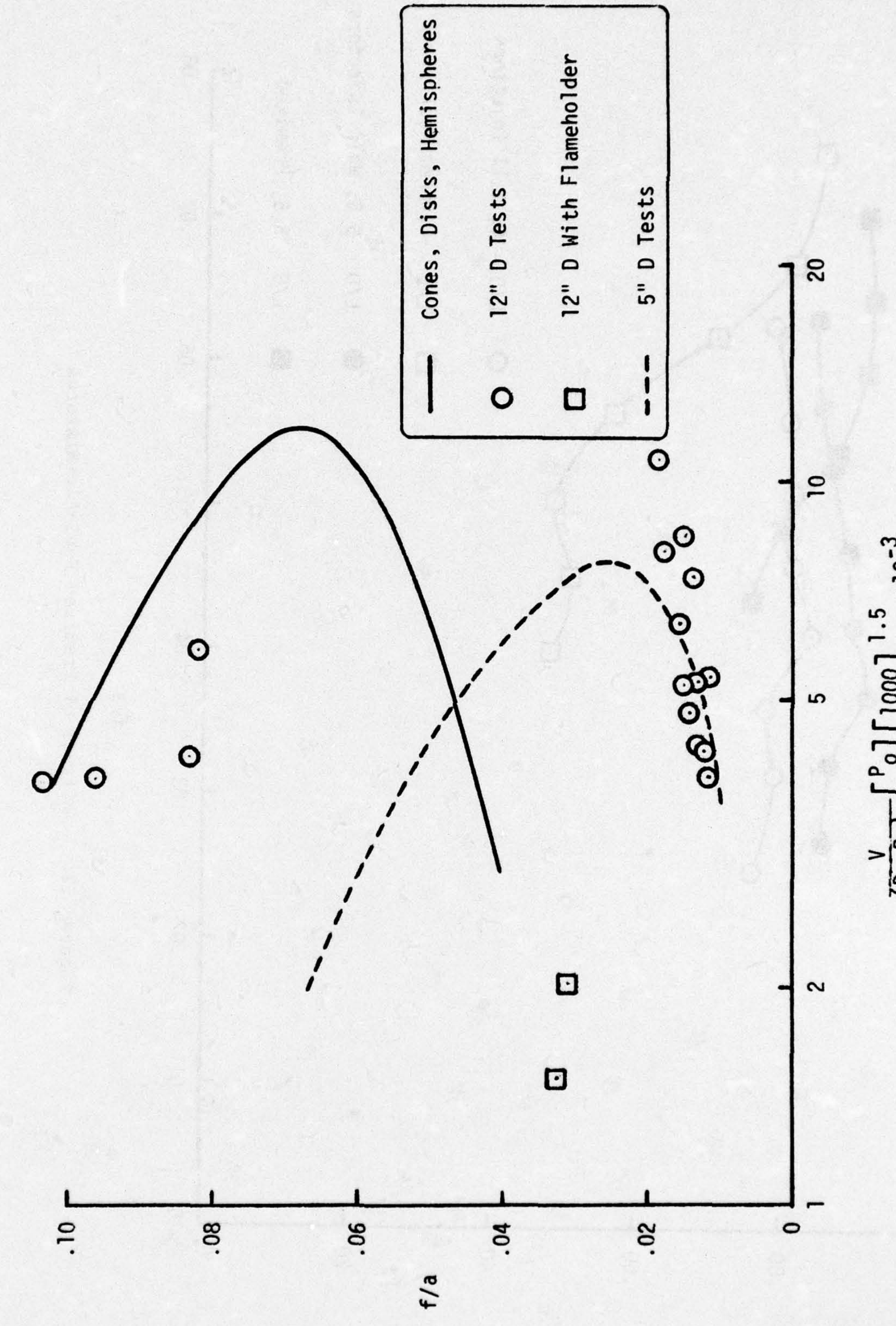

Figure 21. Stability Data Correlation

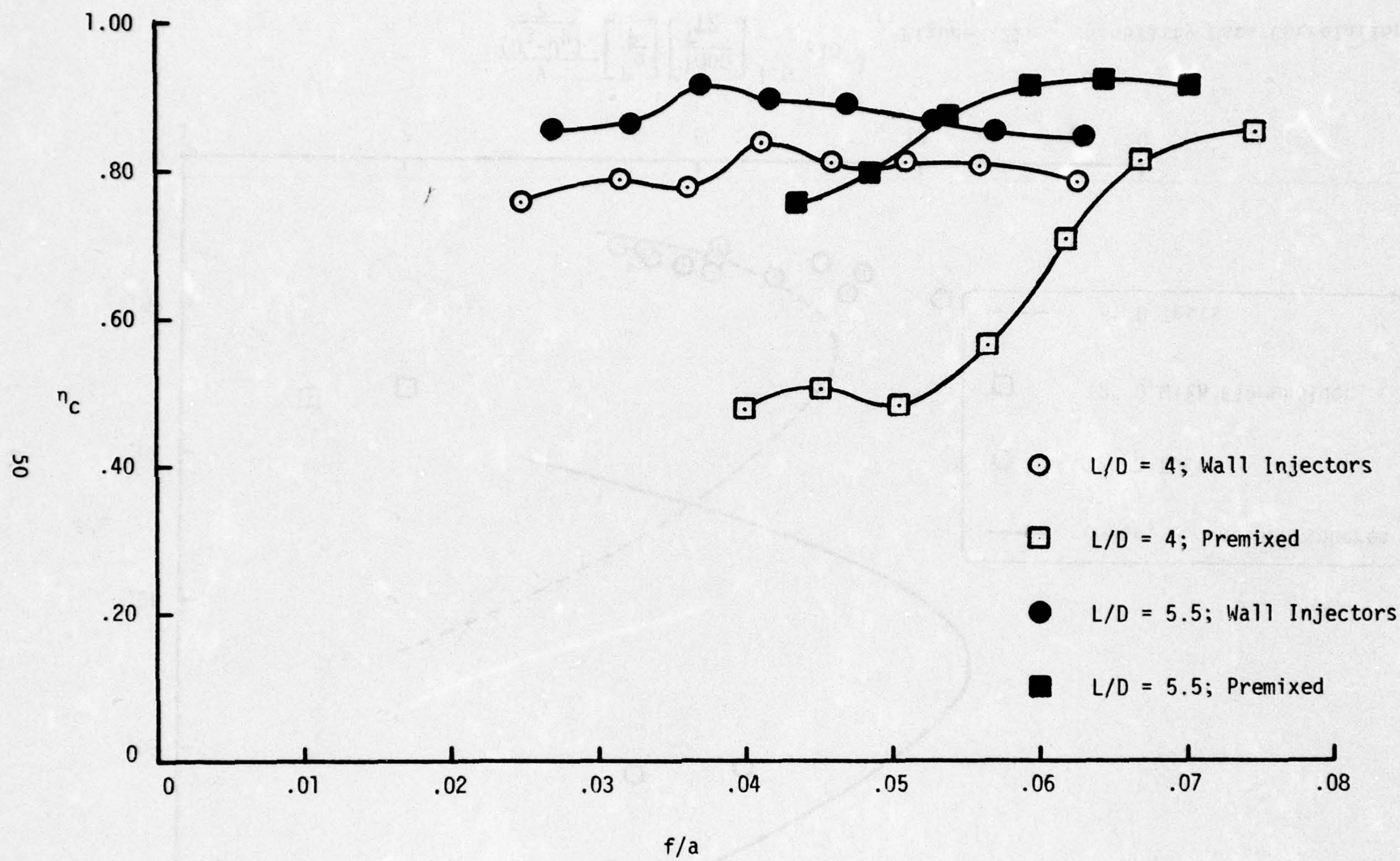

Figure 22. Effects of Premixed Fuel-Air-Mixtures

Figure 23. Burner Severity Correlation: No Flameholder

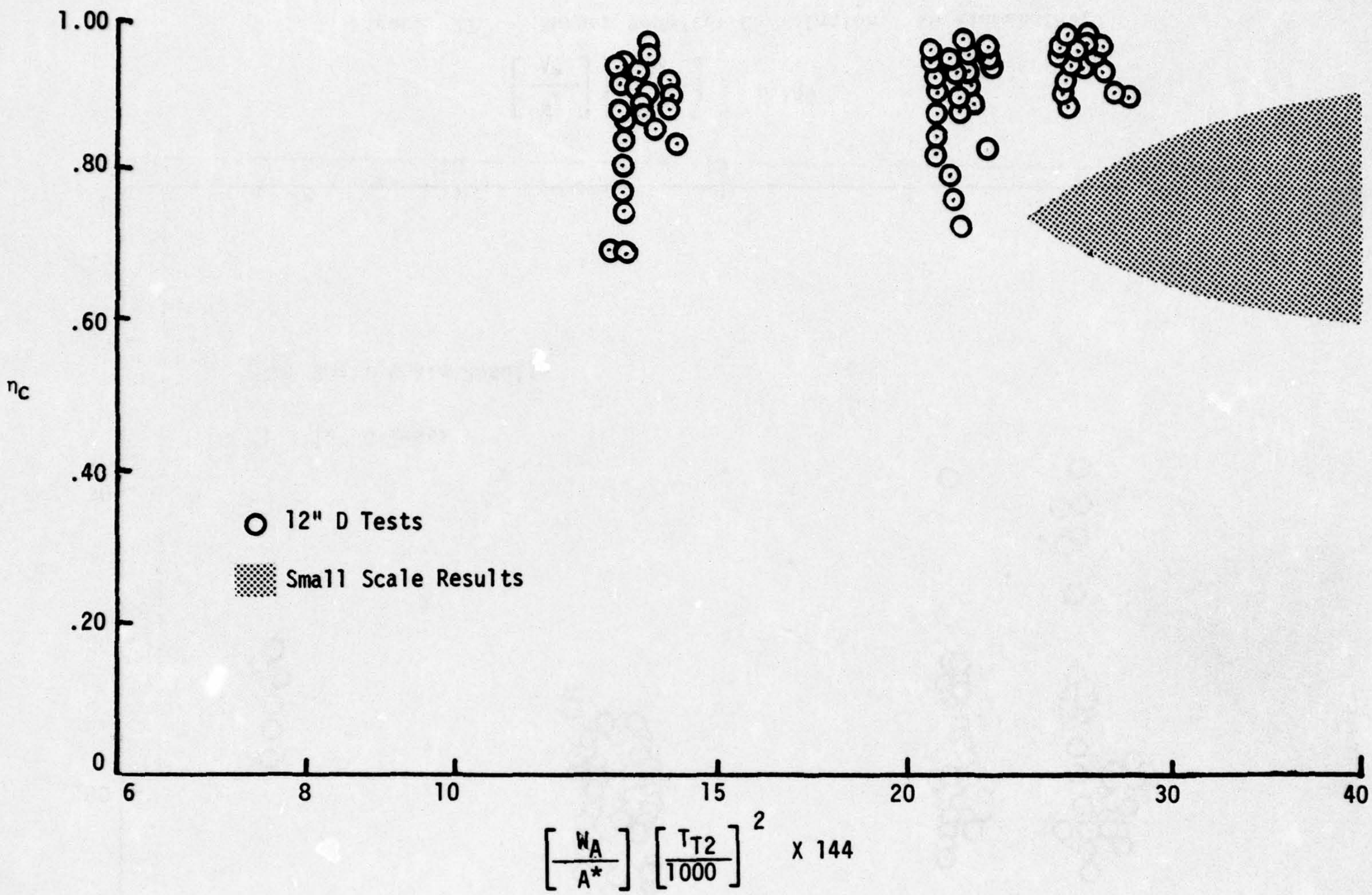

Figure 24. Burner Severity Correlation: Flameholder 25% Blockage

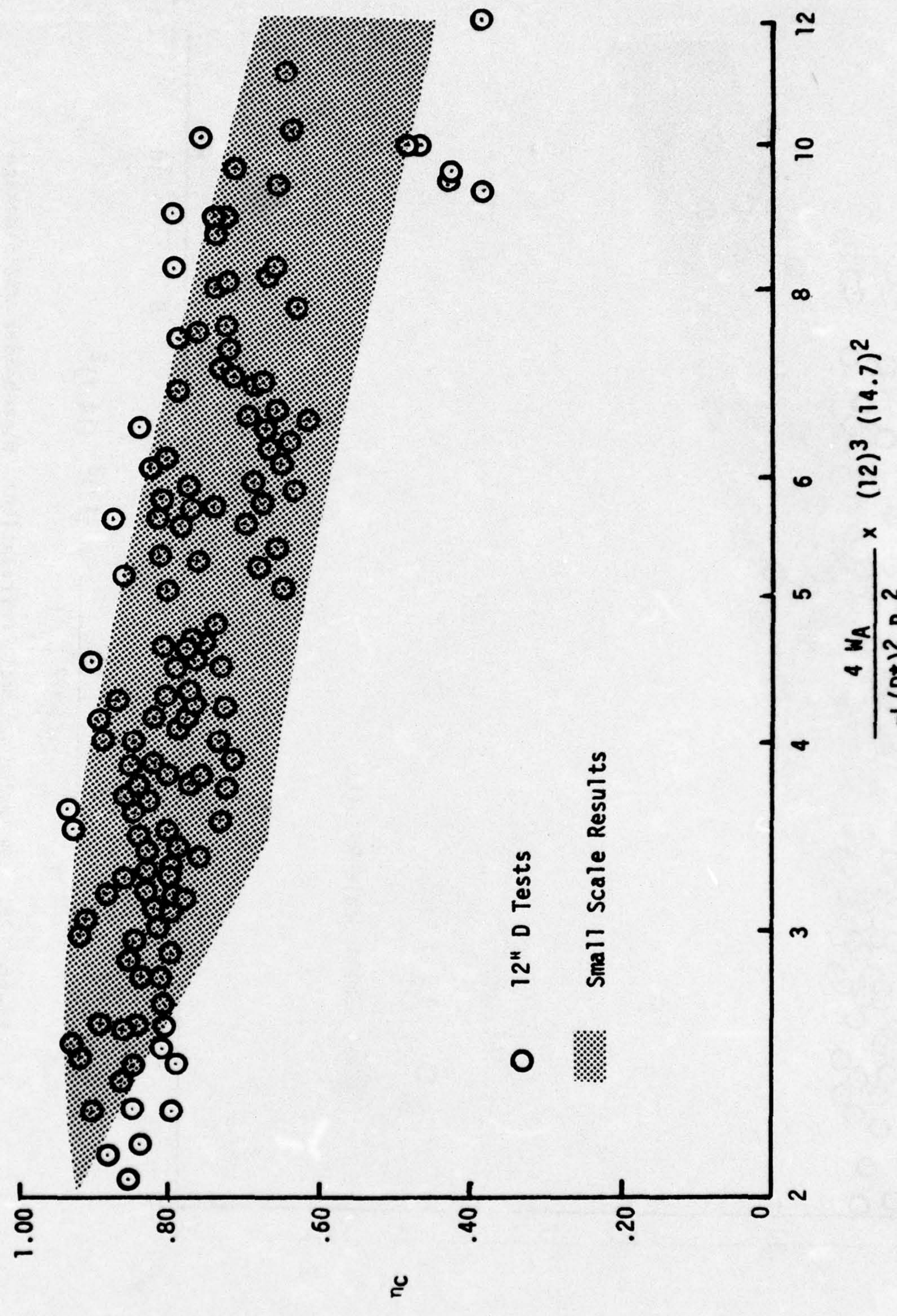

Figure 25. Modified Longwell Correlation: No Flameholder

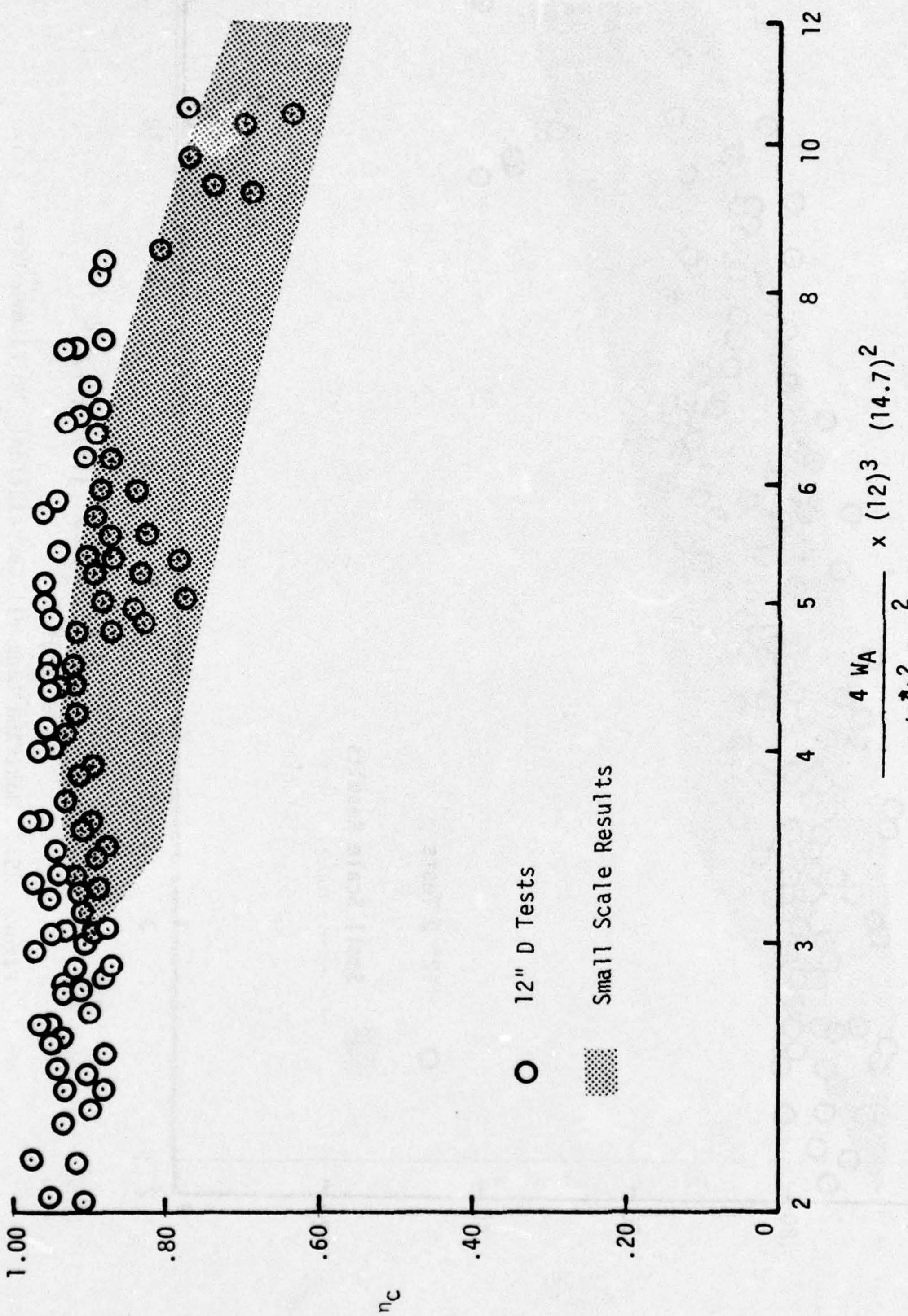

Figure 26. Modified Longwell Correlation: Flameholder 25% Blockage

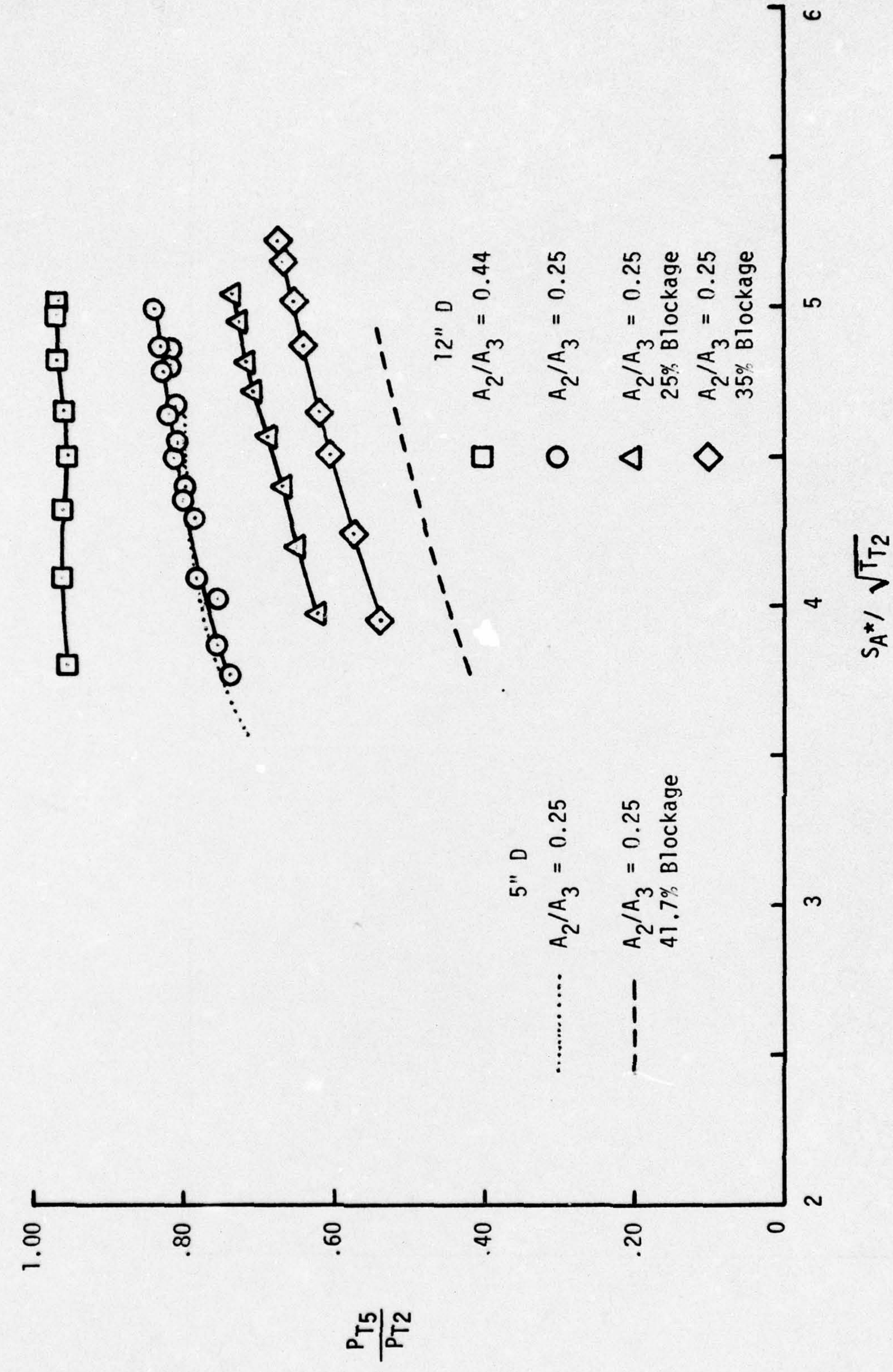

Figure 27. Combustor Pressure Loss

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